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FACULTY OF MECHANICAL
ENGINEERING

BACHELOR THESIS

DESIGN OF SPORT CAR COOLING SYSTEM

2023

MARTIN
KUBÁK

BACHELOR'S THESIS ASSIGNMENT

I. Personal and study details

Student's name:	**Kubák Martin**
Personal ID number:	**491179**
Faculty / Institute:	**Faculty of Mechanical Engineering**
Department / Institute:	**Department of Automotive, Combustion Engine and Railway Engineering**
Study program:	**Theoretical Fundamentals of Mechanical Engineering**
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II. Bachelor's thesis details

Bachelor's thesis title in English:

Design of sport car cooling system

Bachelor's thesis title in Czech:

Návrh chladicí soustavy sportovního vozu

Guidelines:

- Make a research of IC engine cooling system solutions of road vehicles.
- Analyse the cooling possibilities of cooling system individual components of Praga Bohema.
- Design a function scheme of Praga Bohema cooling system and calculate basic design parameters.

Bibliography / sources:

Name and workplace of bachelor's thesis supervisor:

Ing. Vít Doleček, Ph.D. Department of Automotive, Combustion Engine and Railway Engineering FME

Name and workplace of second bachelor's thesis supervisor or consultant:

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Assignment valid until: **19.09.2023**

Ing. Vít Doleček, Ph.D. Supervisor's signature	doc. Ing. Oldřich Vítek, Ph.D. Head of department's signature	doc. Ing. Miroslav Španiel, CSc. Dean's signature

III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

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Date of assignment receipt

Student's signature

Declaration of Authorship

I hereby certify that this thesis has been composed by me and is based on my own work, using only the literature and sources listed in the bibliography.

In Prague 2. 6. 2023 ....

Signature

Čestné prohlášení

Prohlašuji, že jsem svou bakalářskou práci vypracoval samostatně a že jsem uvedl v přiloženém seznamu veškeré použité informační zdroje v souladu s Metodickým pokynem o dodržování etických principů při přípravě vysokoškolských závěrečných prací, vydaným ČVUT v Praze 1. 7. 2009.

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V Praze dne 2. 6. 2023 ....

Podpis

Acknowledgement

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Annotation

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Keywords:	Automotive, sports car, cooling system, thermal management, heat exchanger, heat transfer
Annotation:	The bachelor thesis aims to design an optimised cooling system for Praga Bohema. It begins with research on various cooling system elements used in automobiles. The second part of the research focuses on how heat is created and transferred from the combustion chamber and why it needs to be controlled. The development of the cooling system starts with a description of a mathematical model for heat transfer which focuses on calculations of the cooling capacity of radiators and intercoolers. The last two chapters describe various decisions behind the cooling system development with several different radiators, intercoolers, engine oil thermal management devices and other elements. When possible, these decisions are backed up with results from measurements and outputs from the heat transfer model.

Anotační list

Autor:	Martin Kubák
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Využití:	Optimalizované řešení chladícího systému vozu Praga Bohema.
Klíčová slova:	Automobil, sportovní vůz, chladící systém, chladič, výměník tepla, tepelná výměna
Anotace:	Tato práce cílí na vytvoření optimalizovaného řešení chladícího systému vozu Praga Bohema. Práce začíná rešerší jednotlivých prvků chlazení, které se používají v automobilech. Následuje druhá část reřerše zabívající se se vznikem tepla ve spalovací komoře motoru a jeho následném přenosu a také důvody proč je potřeba toto teplo regulovat. Popisem matematického modelu pro přenos tepla začíná praktická část práce. Model se zaměřuje především na tepelný výkon chladičů a mezichladičů. V posledních dvou kapitolách jsou popsány mnohé kroky, které vedli k rozhodnutím při vývoji chladícího systému, který obsahuje několik různých chladičů, mezichladiče, prvky pro tepelnou regulaci motorového oleje a další prvky. Mnohé z těchto rozhodnutí jsou podloženy výsledky z měření a výpočty v matematickém modelu pro přenos tepla.

List of used symbols

Meaning	Symbol	Unit
Convective heat transfer coefficient	α	[W/m²·K]
Tube thickness	δ	[m]
Fin efficiency	η	[-]
Thermal conductivity of radiator	λ	[W/m·K]
Dynamic viscosity	μ	[Pa/s]
Density	ρ	[kg/m³]
Coefficients for cross-flow radiator	a; b; c; d	[-]
Heat transfer surface	A	[m²]
Specific heat capacity	c	[J/kg·K]
Hydraulic diameter	D	[m]
Darcy friction factor	f	[-]
Correction factor	F	[-]
Fin height	F_h	[m]
Fin density	F_{pul}	[1/m]
Fin width	F_w	[m]
Head pressure	H	[bar]
Thermal conductivity	k	[W/m·K]
Overall heat transfer coefficient	k_A	[W/m²·K]
Flow length	L	[m]
Number of Fin rows	n_F	[-]
Number of tubes	n_T	[-]
Number of passes	n_X	[-]
Nusselt number	Nu	[-]
Number of transfer units	NTU	[-]
Mass flow of ambient air	$\dot{m}$	[kg/s]
Dimensionless temperature change	P	[-]
Prandlt number	Pr	[-]

Meaning	Symbol	Unit
Flow rate	Q	[l/min]
Cooling capacity	$\dot{Q}$	[kW]
Heat capacity rate ratio	R	[-]
Heat resistance	R_A	[K/W]
Reynolds number	Re	[-]
Radiator flow length	R_{fl}	[m]
Radiator thickness	R_t	[m]
Tube inner height	T_{ih}	[m]
Inlet temperature	T_{in}	[K]
Tube inner width	T_{iw}	[m]
Outlet temperature	T_{out}	[K]
Volume flow of coolant	$\dot{V}$	[m^3/s]
Heat capacity rate	$\dot{W}$	[J/s·K]
Coefficient for laminar flow eqn.	X	[-]

List of Acronyms

CAD –	Computer-aided design
CFD –	Computational fluid dynamics
ECU –	Electronic control unit
Eqn. –	Equation
F1 –	Formula 1
HVAC –	Heating, ventilation and air conditioning
ICE –	Internal combustion engine
LMP1 –	Le Mans Prototype 1
OEM –	Original equipment manufacturer
P1 –	First pump
P2 –	Second pump

Table of Contents

1. Introduction

The cooling system is a fundamental component of every vehicle, especially for the racetrack-focused road-legal hypercar such as Praga Bohema. The cooling must support the powerful engine under a full load for a prolonged time on a racetrack in all conditions so that the vehicle does not lose power. Moreover, it has to cooperate with an HVAC system which secures comfort in a passenger compartment. Preventing unnecessary emissions and fuel consumption that could occur if the engine was working outside of its operating temperature range is also of great importance.

At the beginning of the thesis, the Praga Cars company and the vehicle Bohema are portrayed to offer a piece of background information. It is followed with a description of the main objectives of the thesis as well as its constraints and various challenges which had to be overcome. The research on how heat is created inside the internal combustion engine and why it needs to be regulated follows. After that, the depiction of the cooling system circuit serves as an introduction to the cooling system problematics. The central part of the research segment of the thesis consists of a description of various elements of cooling systems used in automotive. Their function and how they operate are presented with various types of said elements and their benefits and downsides. Finally, the research concludes by discussing how hypothetical vehicles would perform under presented scenarios based on the elements used in their cooling systems.

The second part of the thesis begins by presenting equations used in an analytical heat exchange model. It is followed by the description of the cooling scheme of Praga Bohema, which was designed to sustain the engine at full load under all scenarios. The cooling system must fit into the current vehicle package, replacing the prototype solution. The most critical decisions regarding the cooling system development and the assumed cooling capacity are backed by calculations in the previously presented model. Furthermore, it includes the demonstration of the modifiability of a cooling system which can be done during on-track testing. In the end, the decisions regarding the design and flow configuration for the radiator, intercooler and engine oil thermal management are presented.

1.1 Praga

The company's history began in Czechoslovakia in 1907, making it one of the oldest automotive companies in the world. Over its existence, Praga designed and manufactured various types of machines, from automobiles, motorcycles, buses, and trucks to aircraft and helicopters. The most famous model is the Praga V3S, made in many variations and exported worldwide. Moving on to the 21. Century the company's Praga Cars division switched its focus towards the motorsports industry with its popular Praga R1 track-only racecar or the newest project Praga Bohema. [1]

1.2 Bohema

Bohema is a road-legal hypercar built to achieve the best racing experience and behave well on a race track. To accomplish that, it must be as light as possible while having good aerodynamics and a powerful powertrain. Being a road-legal car bears challenges in the form of the need for homologation, passenger compartment comfort and other requirements which would not be present if Bohema was built solely for a race track. This means the car must comply with emission, safety, electronics and many more regulations. For comfort, an HVAC system, luggage area, interior design, and other features inevitably compromise race car characteristics. Not to mention that the car must be aesthetic and unique to perform well in the market where much larger companies with more resources and manufacturing capabilities are the competition. Below are some overall parameters and a picture of the vehicle taken from the official website in Figure 1-1. [2]

Weight: 982 kg
Downforce at 250 km/h: 9000 N
Mid-engine layout with rear-wheel drive
Spark-ignition twin turbocharged internal combustion engine
Displacement: 3.8 l
Cylinders/valves: 6 / 24
Engine power: 700 bhp at 6,800 rpm
Engine torque: 725 Nm from 3,000 to 6,000 rpm
Top speed: 300+ km/h

Figure 1-1: Official photo of Praga Bohema. [2]

2. Aim and Constraints of the Thesis

The bachelor thesis aims to design an optimised cooling solution for the Praga Bohema, focusing on obtaining the maximum possible cooling capacity. At the same time, the solution should be semi-modular to allow changes which should be tested on a race track with the motivation that only after a series of testing the very best performance can be extracted from the designed cooling system. The development focuses on the engine coolant with a lesser concentration on thermal management of the engine oil, charge air and the HVAC elements.

In the beginning, it is necessary to present the constraints and challenges influencing the choices made for the cooling system and its various parts. Most of these issues originate from the vehicle concept and the simple fact that the cooling system will not be placed into a new vehicle, but it must work only with a package available inside the current geometry.

2.1 Bohema design philosophy

The three central values of Bohema include low weight, high engine power and aerodynamic performance, which are the keys to designing any race car focusing on racetrack performance. It also has to ensure the comfort of passengers and emission and fuel consumption control which are qualities race cars do not possess. Generally, a car can be designed focusing on maximum speed, drag racing, lap time, fuel efficiency, low emissions and many more. It is a question of compromises where each way negatively affects the other. The cooling package follows the same rules, making it challenging since Bohema must behave as a passenger and a race car at the same time.

For racing, the targets were set to sustain the car in extreme weather conditions under a full engine load for 45 minutes on the racing circuit.

Most limiting for the cooling was the fact that inlets and outlets for the ambient air towards the radiators and intercoolers are shaped with aerodynamic and aesthetic goals in mind. This is not necessarily the best for maximum cooling capacity. Only the internal surfaces of the ambient air ducts could have been modified, but their development is not part of this thesis.

2.2 Vehicle Packaging

The package envelope for the new cooling system could not be enlarged compared to the previous prototype solution. On the contrary, due to the changes in outer surfaces, most of the previous OEM radiators and intercoolers could not be used anymore, and their replacement had to be found.

It is essential to describe the position of the primary radiators. In Figure 2-1 from the official car website, the location of the sidepod where the radiators and intercoolers are placed is marked. [2]

Figure 2-1: Bohema on a racetrack with red marked sidepods. [2]

Praga Bohema is equipped with a VR38DETT V6 gasoline internal combustion engine made by Nissan which can be found in the Nissan GT-R. [2]

The first thing to note is that the Nissan GT-R has the engine in the front, while Bohema uses a mid-engine layout. Therefore, some of the inlets and outlets for the coolant are positioned in the back of the engine, which is not ideal for piping. Moreover, since Praga is not the engine manufacturer, its precise 3D model could not be used to create a more detailed model for heat exchange with modelled internal coolant flow.

The thermostat, expansion tank, heater, and condenser were other predefined components from the powertrain that affect the cooling and cannot be changed. The condenser is situated in the left sidepod, and another challenge was finding a way to ventilate the engine bay through the sidepod.

Furthermore, only changing an air-to-air intercooler and its piping from turbochargers into the intake manifold for the charge air could have been done. The goal was to enhance the cooling capacity of this system as well.

Most of the engine oil system and the components responsible for its circulation remained the same, and only the parts responsible for its thermal management could have been changed.

2.3 Operating conditions

One of the tasks was to cool down the working fluids at maximum temperatures for at least 45 minutes to ensure the engine does not lose power due to working outside of its optimum temperature range and the fluids do not degrade at faster rates or face other issues.

Coolant:	Water:Glycol mixture - 50:50	Maximum temperature:	95°C
Engine Oil:		Maximum temperature:	115°C

The minimum temperature was not of great concern for coolant since it has a mechanical thermostat which opens at a set temperature. Keeping the glycol mixture as a working fluid was recommended to ensure the vehicle could operate below 0°C. An analysis of how the cooling power would change if the glycol mixture were replaced with a pure water-based solution is presented in the final chapters of the thesis. For the engine oil, the temperature should be lower than the coolant inside the engine during the race regime of the car.

For the charge air, the aim was to cool it down as close to the ambient temperature as possible.

These two extreme ambient air temperatures were set for the external weather conditions directly influencing the cooling system.

Maximum temperature: 50 °C   Minimum temperature: -20 °C

2.4 Outer Constraints

One of the essential constraints of the thesis execution is not to leak any internal information and confidential data in general. To do so, the values regarding flow rates or cooling capacities will be presented in percentages of maximum or selected values. In some cases, written explanations will be used instead of pictures and diagrams from CFD, CAD, and other software or measurements. However, the continuity of the thesis or its value in describing the tasks and solving processes will not be hindered.

An important factor was the tight schedule regarding both the deadline for the thesis and the need for the cooling package to be ready on the car for the summer testing season. This meant that not every element of the cooling system could have been developed by the company, and for elements like water pumps, valves, and liquid-to-liquid heat exchangers, the suppliers had to be found.

Another challenge is that the preliminary prototype cooling system was designed for lower engine power and slightly different packaging, so many elements had to be redefined for the system to remain efficient.

Also, since a small-series production of 89 cars is planned, the expensive technologies that sometimes appear in the cooling systems of F1 race cars or other high-end motorsport series like LMP1 produced in lesser numbers could not have been used.

In a small automotive company with such a low number of planned vehicles, finding manufacturers able to supply custom coolant and oil radiators, intercoolers, and other devices proved challenging.

3. Engine thermal management

The internal combustion engine is the source of most of the heat created inside the vehicle and the main element which requires thermal management. Therefore, it is essential to explain in a simplified manner how the heat is created, how it can be categorized and what would happen if it was poorly managed.

3.1 How the heat is created inside the ICE

This segment will focus on a 4-stroke spark-ignition turbocharged internal combustion engine since it powers the Bohema.

To get the mechanical power of the ICE, we need to secure reciprocating fuel and air mixture combustion in a cylinder. Gasoline is the fuel supplied by the fuel pump and carried within a vehicle in a fuel tank. The oxygen needed for combustion comes from the ambient air, which supply is further enhanced by a turbocharger, a compressor driven by a turbine utilizing the enthalpy of exhaust gas. This allows for increased air mass flow, resulting in more fuel injection given the same air-fuel ratio, leading to more engine power while utilizing part of the waste energy of the exhaust gas.

The combustion occurs when an electrical spark plug ignites the air-fuel mixture, usually before the piston reaches its top dead centre. In an ideal case with stoichiometric combustion, the air-fuel mixture is wholly transformed into exhaust gases and the chemical energy contained in the fuel is fully released as heat. This results in a rise of pressure and temperature, which drives the cylinder towards the bottom dead centre and through the connecting rod and crankshaft, the reciprocating linear movement is transformed into rotation.

This heat directly released by combustion is increased by the friction loss of the piston in a cylinder liner and other moving elements like the crankshaft and camshaft. Additionally, the turbocharger compresses the ambient air, and the cylinder compresses the air/fuel mixture, adding heat to the system.

In Figure 3-1 below, a picture of a general single-cylinder engine with coloured arrows and a chart showing how the chemical energy from the combustion process is converted can be seen. It is important to note that this is an approximation for a single-cylinder, and the exact ratio of how the heat energy balance is distributed varies depending on many factors [3]

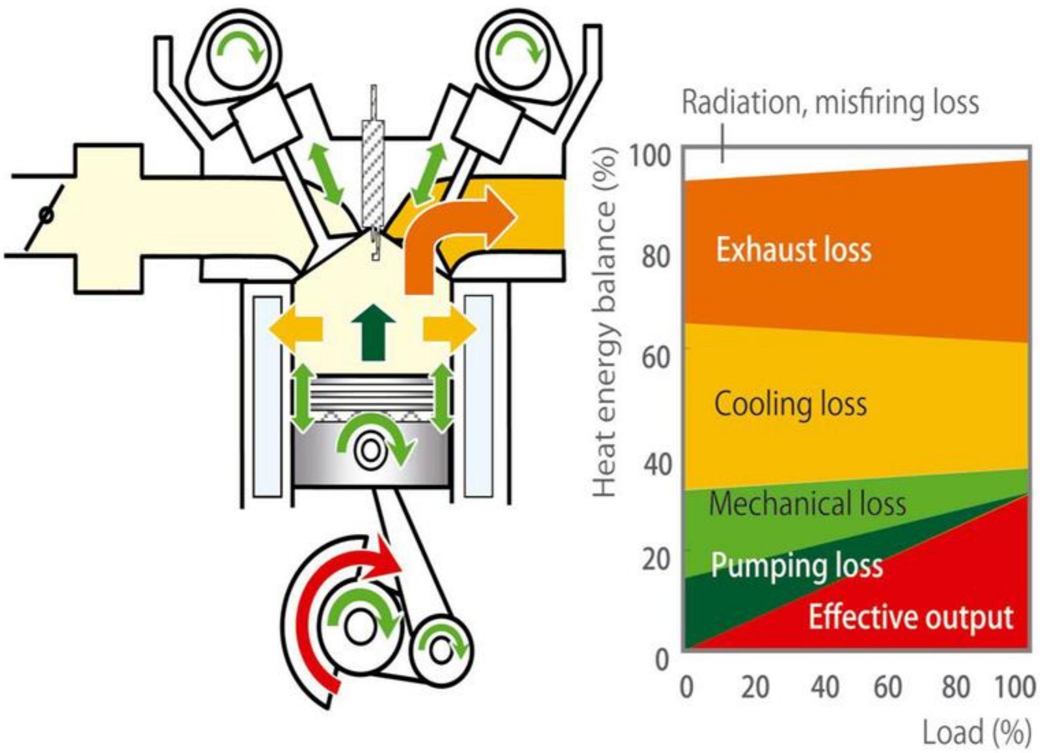

Figure 3-1: Heat energy balance of single-cylinder ICE. [3]

Exhaust loss is the energy contained in exhaust gases. In turbocharger portion of it can be reused.
Mechanical loss can be divided into friction resulting in more heat and a loss required to power the water and engine oil pumps, alternator and other auxiliary devices via the drive belt connected to the crankshaft. The latter, on the other hand, supports the cooling system. Pumping loss is the power needed to move the cylinder, for example, to expel the exhaust gasses. Effective output is the engine's mechanical power transferred to the drivetrain. The cooling loss is the energy transmitted into the coolant that must be dissipated into the atmosphere. [3]

Determining how much mechanical and exhaust loss is eventually transferred into the coolant was not possible since the development to increase the engine power was carried out during the same period as the one for the cooling system.

Also, for example, the friction part of the mechanical losses ends mainly in the lubrication system. The turbocharger is cooled down by coolant and connected to the lubrication system. The heat from the exhaust, especially from the catalytic converter, can be transferred into the coolant if the heat is accumulated inside the engine bay.

3.2 Why ICE needs thermal management?

When a system generates heat without the same amount being rejected, the heat accumulates. The accumulation can be represented by the increase in the engine block temperature, which will continue until the cooling system manages it. The opposite can happen if the heat is rejected more than created. For example, if the engine was in a freezing environment while running on low load.

Several of these heat-related issues caused by an engine operating outside its operating temperature range are presented. Mitigating these issues is vital to maintain the engine's performance, reduce emissions, fuel consumption and wear.

3.2.1 Mechanical-based issues

The thermal expansion can negatively influence the tight tolerances in the engine. This can result in higher component wear and stress, which can cause component damage and decrease engine performance. This is challenging in a combustion chamber where the space between the cylinder liner and piston rings needs proper sealing. The cylinder liner is designed to have the desired shape under predetermined operating temperatures and pressures to overcome the thermal expansion influence on tolerances. The so-called orders of bore distortion can be observed, and adjusting the sealing to account for them is crucial. For the most common cylindrical pistons, 3 of these orders of distortion are illustrated in Figure 3-2 below. [4]

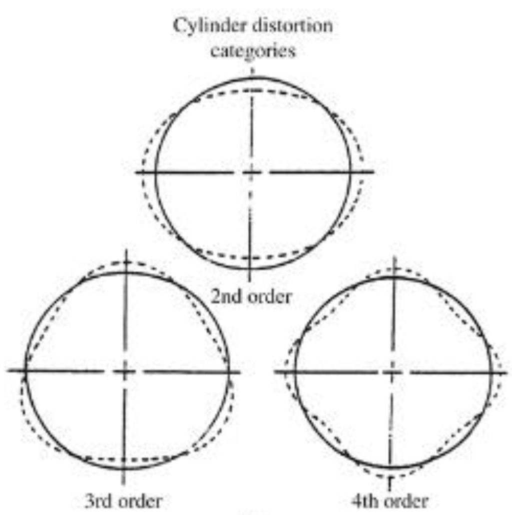

Figure 3-2: Cylinder distortion orders. [4]

3.2.2 Abnormal combustion

The engine knock is caused by the spontaneous ignition of a large amount of air-fuel mixture, which causes a significant increase in pressure and the formation of pressure waves. It occurs before the flame propagation itself. It is influenced by the intake air temperature, which depends on a turbocharger and intercooler.

Surface ignition can occur before or after the combustion when a part of the combustion chamber reaches temperatures high enough for it to happen. The deposits in a combustion chamber or, for example, an overheated valve can be the place of this phenomenon. In this sense, it can be partly prevented by a properly working cooling and lubrication system and the intercoolers. [4]

3.2.3 Coolant and Engine oil related issues

The coolant and engine oil must be kept in certain pressure and temperature operating ranges. In an ordinary car, the coolant usually consists of a mixture of water and glycol, allowing it to operate in freezing conditions. However, a water-based solution can replace the coolant mixture with anti-fouling and anti-corrosion additives for many race cars or as an upgrade for ordinary cars. This can increase the cooling capacity, but the engine cannot be kept in freezing temperatures since it would lead to ice formation, damaging it.

The coolant will boil when surpassing the maximum operating temperature at a given pressure. To prevent damage from the pressure to the coolant lines or the engine itself, the excess coolant vapours will travel into an expansion tank where a pressure relief valve will open to maintain the pressure.

The primary function of engine oil is to lubricate the engine, but it performs the cooling role in places where both functions are needed. For example, engine oil is sometimes used to cool down the cavities under or inside the piston. We can speak of a cold start when the outside temperatures are low. It should not be tried to run the engine under full load immediately but instead, slowly increase the temperature first to prevent wear and incorrect combustion. These problems arise due to the high viscosity of the engine oil at low temperatures when it cannot distribute the heat in the engine well, and it cannot ensure proper lubrication and smooth sliding of piston rings in the cylinder liner, for example. [4]

For the high temperatures of the engine oil, the main problem lies in thermal degradation, which causes oil thickening and the creation of corrosive acids. It will faster clog the oil filter and damage the engine due to corrosion and improper lubrication.

4. Cooling system components

This chapter presents the research regarding various elements of vehicle cooling systems, including the engine used in Bohema with its various coolant inlets and outlets.

Figure 4-1 represents the cooling scheme from the perspective of the coolant. It simplifies the existing system with all main cooling lines and system elements used in Bohema and many other sports cars. The deaeration lines are not fully displayed. The engine has the inlets and outlets marked with a letter which will be later explained with a more detailed engine model.

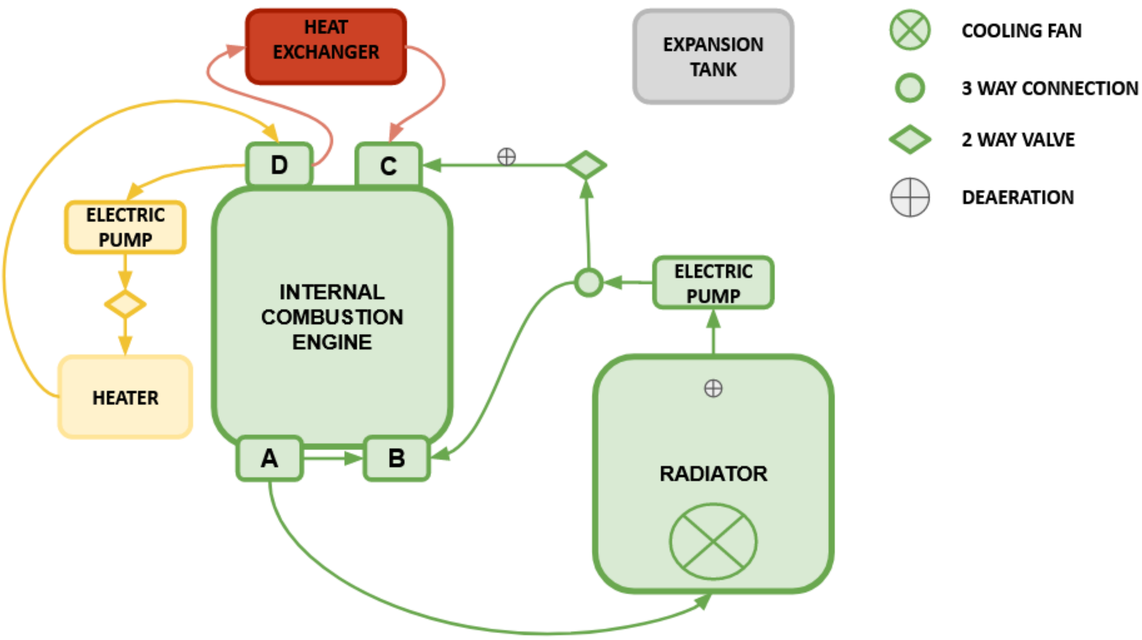

Figure 4-1: Cooling system diagram.

The green colour represents the core of the cooling system and includes main parts like the ICE, radiator and an electric pump. The circuit ensures that the coolant dissipates heat into the ambient air.

The yellow-coloured elements like the heater, electric pump and 2-way valve primarily heat the passenger compartment.

The red circuit with a heat exchanger is responsible for the thermal management of engine oil by cooling or heating it with a coolant.

Finally, the supportive grey circuit with deaeration valves and expansion tank ensures that air is kept out of coolant lines and the coolant can be filled in and easily distributed.

4.1 Internal combustion engine

Looking at the engine itself is essential to describe the cooling system and its circuits. Figure 4-2 provides a more detailed representation of the engine than Figure 4-1.

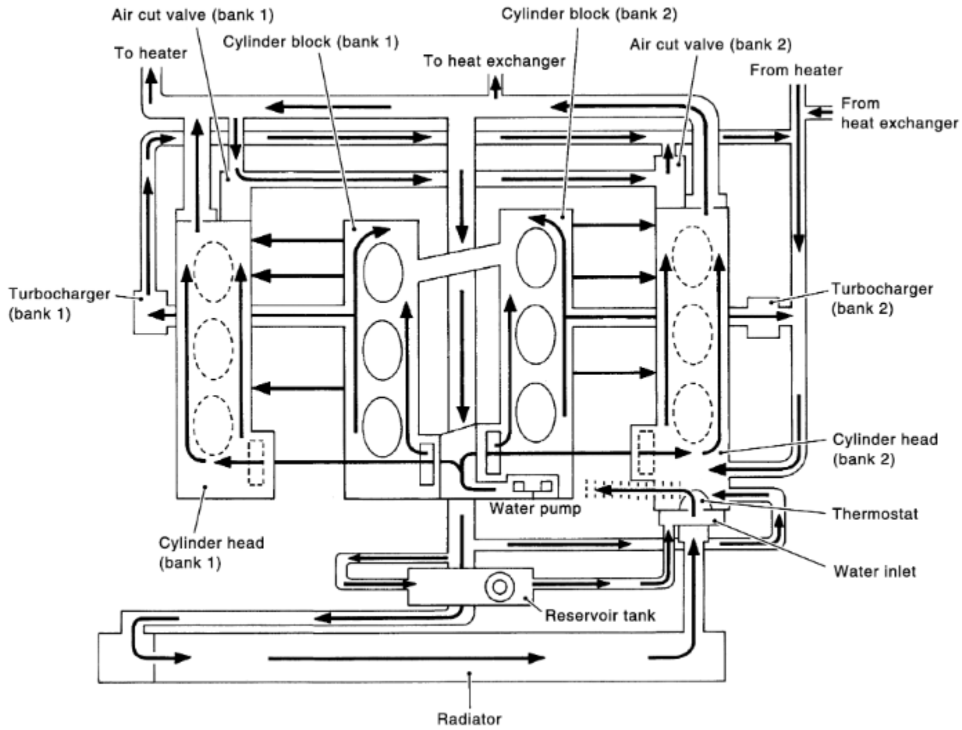

Figure 4-2: Engine diagram provided in Nissan service manual. [5]

In Figure 4-2, the inlets and outlets for the coolant from the engine can be seen. The letters in Figure 4-1 serve as their representative for more efficient work with the cooling scheme. Letter A represents the engine's main outlet, where the hot coolant carries away the heat from the engine block, cylinder head, turbochargers and other elements towards the radiators. In addition, from outlet A towards inlet B, there is a small coolant line which serves as a recirculation line which is opened when the thermostat located in inlet B is closed. It allows the engine to retain the heat from combustion when needed. The main element in the letter B is a mechanical thermostat which is the control element that regulates whether the coolant will circulate inside the engine or in the whole system with radiators. There is also a small line from the reservoir tank towards the thermostat. This small inlet completely bypasses the thermostat allowing the deaeration of the thermostat and return of the coolant to the engine. The mechanical water pump is located behind the thermostat. [5]

Many small inlets and outlets can be seen on the other side of the engine in Figure 4-2. They are represented with letters C and D in Figure 4-1, where they are divided mainly for clarity of the scheme. These inlets connect to a coolant-engine oil heat exchanger, heater and turbochargers. [5]

4.2 Thermostat

A thermostat is the main control element of the cooling system. When the temperature rises above a predetermined value, the engine inlet from the primary radiators begins to open while the recirculation line closes. The same process but in reverse, repeats when the coolant temperature begins to decrease.

A most common thermally/mechanically actuated thermostat works on a principle of a small container with wax which, as it heats up by the passing coolant, starts to melt and expand, applying a force which overcomes a spring which keeps one of the inlets open and the other one closed. The process reverses as the coolant cools down due to the wax transforming into its solid state. The average temperature when the thermostat begins to open is around 80 °C depending on its design. This is lower than most of the engine's effective operating range since it takes some time for the thermostat to open. Figure 4-3 shows a typical mechanical thermostat with the primary valve for the main inlet and the secondary valve for recirculating. The wax is contained within the charge cylinder. [6]

The electrically assisted thermostat is a clever solution to keep the engine at its operating temperature longer by increasing the opening temperature. Integrating a small ECU-operated heater helps to keep the engine in its optimum temperature range based on the engine map. When needed, the heater starts melting the wax, opening the thermostat much faster than if it was not present. [7]

There are also electrical thermostats that offer the best control over the engine temperature since they are not dependent on it.

One of the last alternatives is to remove the thermostat. Many racing vehicles like NASCAR or F1 do not need it because the cars never truly experience the cold start and the coolant, and therefore engine temperature can be set before the race by external devices. For a road-legal car like Bohema, this is not an option. [8]

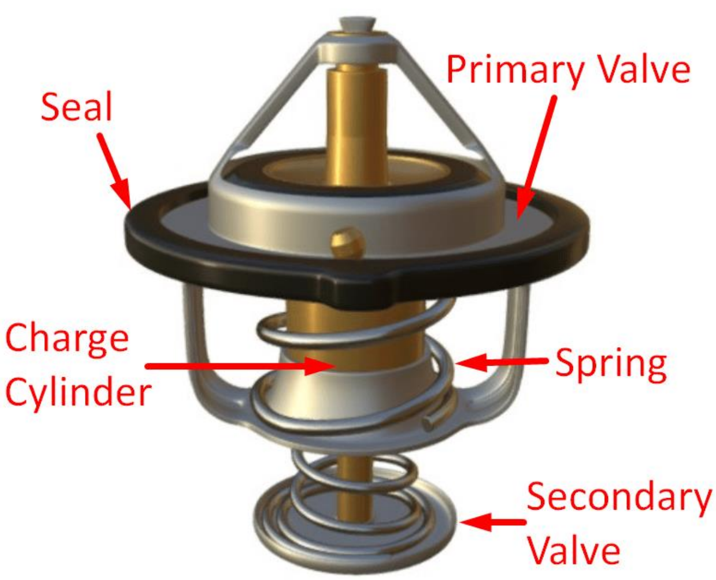

Figure 4-3: Characteristic mechanical thermostat. [6]

4.3 Water pump

A coolant pump, better known as a water pump, circulates the coolant inside the cooling circuit. It is a critical element in the cooling system, and therefore it needs to be as reliable as possible since if it fails, the engine overheats. Furthermore, as will be discussed later, it is desirable for better heat transfer to select a water pump capable of keeping the coolant velocity in radiator coolant tubes high enough for the liquid to be in a turbulent state.

Their construction can be described as a radial impeller with curved blades driven directly by an in-build electric engine or by a drive belt connected to the crankshaft. The impeller can be made from plastic or metal, and its design is open or closed depending on the required coolant flow and pressure and, therefore, the predicted stress of the component. Figure 4-4 depicts several types of impellers available on the market. [9]

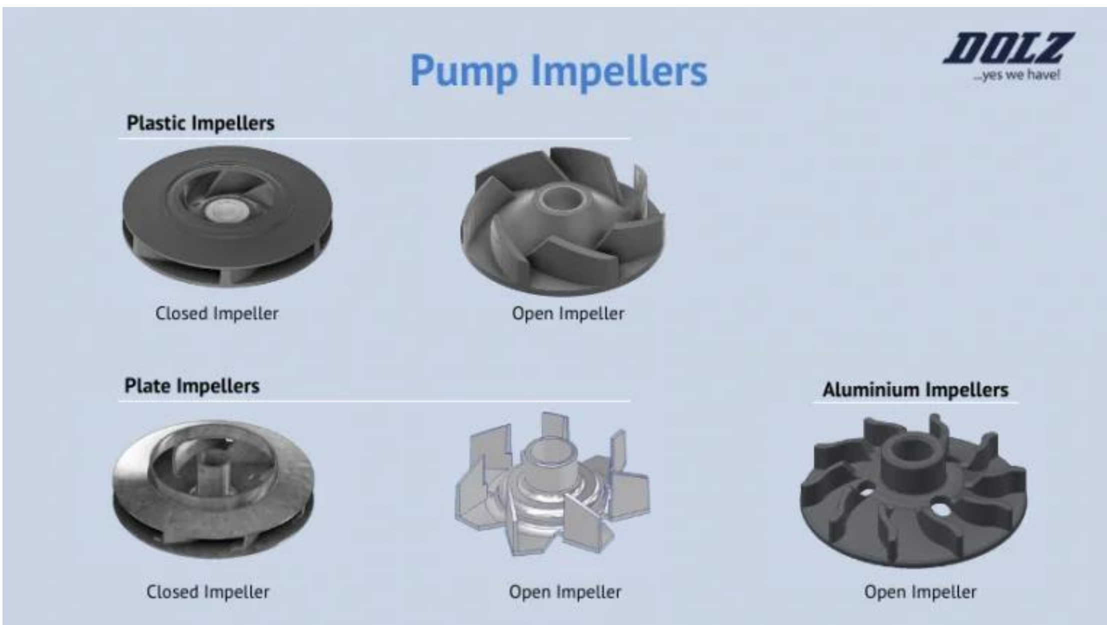

Figure 4-4: Types of water pump radial impellers. [9]

Mechanical pumps driven by a drive belt are usually located inside the engine. They depend on the engine speed, making it problematic to control the coolant temperature. The benefit is their smaller size because the driving element is the engine itself. They can work with higher pressures and flow rates and are arguably more reliable overall. It is possible to use a variable pump still driven by the drive belt but with ECU control to secure a more optimum engine temperature. [10]

Vehicles can have several auxiliary pumps depending on the cooling system's complexity. For example, to compensate mechanical pump when the engine speed is low or to force the coolant to devices like a heater or liquid-to-liquid heat exchanger. For this task, an electric pump is ideal since it can be fully controlled independently on the engine and can be placed nearly anywhere in the car. [10]

4.4 Coolant valves

The coolant valves in the automotive industry are usually based on a solenoid that, when powered, generates a magnetic field which opens or closes the valve. This is along the thermostat and a coolant pump, another option to control the cooling system. An automotive coolant valve's required properties are to be reliable and light, offer low pressure drop, and work under the coolant's temperature range. Figure 4-5 shows an inline 2-way valve designed for high-volume flow and low-pressure loss. The valve can be more complex, with multiple inlets and outlets and even more than one solenoid to control them. A fail-safe position can be selected to mitigate the damage in case of solenoid failure. [11]

Figure 4-5: Inline 2-way coolant valve. [11]

4.5 Coolant

The coolant is a medium that transfers heat from the ICE into the atmosphere through the radiator. It is well known that pure water is one of the best liquids for heat transfer. However, several challenges need to be solved in a coolant, no matter how good its heat transfer parameters are. The first of them is fouling and corrosion. For example, if we used tap water, the minerals and other substances diluted inside could corrode the metal surfaces of the engine and radiator. In addition, layers of sediments could form in tight radiator tubes resulting in decreasing cooling performance due to its insulating properties and blockage. Chemical additives nowadays counter both issues.

Another challenge is the temperature range when the coolant is liquid. In a cold environment, coolant can freeze and destroy our engine. However, under high-temperature conditions, water would boil, which would result in a pressure rise and opening of the pressure cap resulting minimally in the vehicle not being to drive again until it cools down.

This can be solved by mixing the water with ethylene glycol, which has a larger temperature range for its liquid state. Surprisingly enough, pure ethylene glycol freezes at around -13 °C, but when mixed in a ratio of 40:60 water: ethylene glycol freezes at -52.8 °C, allowing this composition to work almost anywhere on a planet. On the other side of the temperature range, it boils at 111.1 °C in atmospheric pressure, which can be further postponed by increasing the pressure. This can enhance heat transfer because of the greater temperature difference between the coolant and ambient air if the engine is designed for it. [12]

4.6 Radiator

A radiator is an ambient air-to-liquid crossflow heat exchanger where most of the heat produced by ICE is dissipated into the atmosphere. It usually consists of many thin oval tubes through which the coolant flows and a finned structure between them. The finned structure offers a large surface area for the ambient air to ensure a good heat transfer. Moreover, the finned structure serves as a turbulator meaning that the ambient air passing through will stay turbulent even at low velocities, again for better heat transfer. There are various types of finned structures with different densities and dimensions, each with unique characteristics of pressure loss depending on mass flow. Choosing the best one requires running tests and simulations, and apart from their thermal performance, the weight and cost can also be a factor. This type of radiator is called Tube and Fin, and it is usually made from aluminium.

In Figure 4-6, on the left, the coolant tubes are visible; on the right, there is the typical finned structure for the ambient air. Both figures are from the same Tube and Fin radiator core.

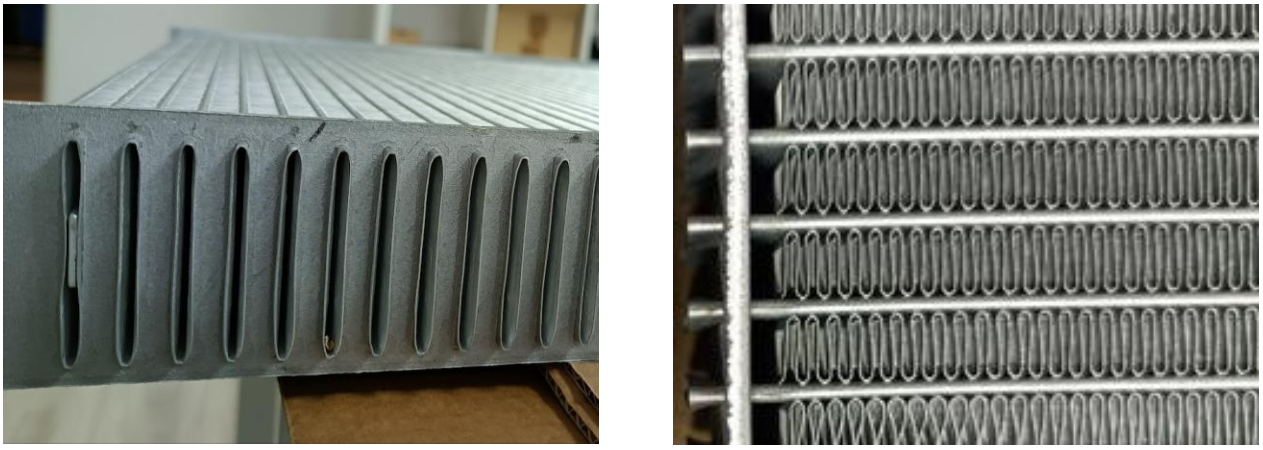

Figure 4-6: Visible coolant tubes and finned structure of the radiator.

One high-performance alternative uses no fins but large quantities of small tubes, called microtubes for the coolant flow. They can be as small as 0,2 mm in diameter. Compared to the Tube and Fin type, this keeps the ambient air pressure drop lower while having the same size, coolant flow and cooling capacity. It can be potentially beneficial for the vehicle in lowering the aerodynamic drag and downscaling the cooling fan or the radiator itself. This can reduce weight, space or required power for the fan. Moreover, the tubes can be made from polymers that are more resistant to damage than if they were from aluminium. A radiator like this can be seen in Figure 4-7, which shows the small tubes. The downside of this radiator type is the much higher cost per unit. They can be found in high-performance automotive racing categories like F1 or LMP1, where the cost has a much lower priority compared to the performance. [13]

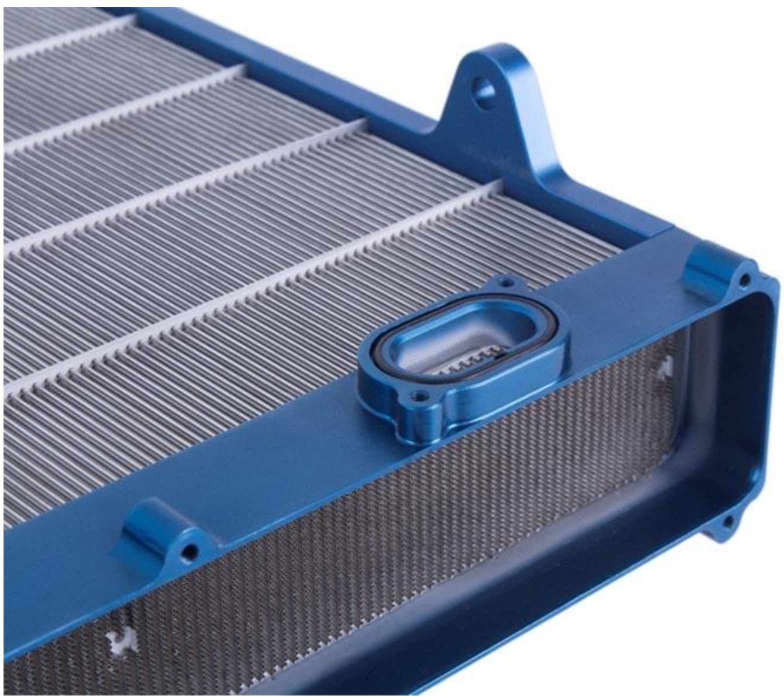

Figure 4-7: Microtube radiator core. [13]

4.6.1 Radiator end tanks

Apart from the radiator cores, it is also important to study the radiator end tanks and how they can change the flow through the radiator core.

End tanks can be placed so that coolant passes the radiator horizontally or vertically, where the difference in density of warm and colder coolant can play a small role in flow distribution. However, it is relatively insignificant compared to the influence of the forced volume flow by the water pumps used in cars. The difference in performance often comes down to the available space for the radiator and its end tanks in the sidepod or under the vehicle's hood. It is much better to have the radiator core exposed to the airflow than the end tank.

The difference in performance can also be based on the position of inlets and outlets in the end tanks. For example, the inlet and outlet can be placed only on the upper side of the end tanks, with cooling tubes going horizontally through the radiator core. In theory, most of the flow will take the shortest path, and the rest of the radiator will be less efficient. This is visualised in Figure 4-8. Placing the inlet and outlet diagonally could be better to distribute the flow more evenly across the core. Nevertheless, without a proper 3D CFD simulation model, all of this cannot be properly predicted since it depends on variables like the pressure and flow rate of the coolant, the size and shape of the radiator end tanks and the coolant tubes. It can also often be dictated by the package of the vehicle.

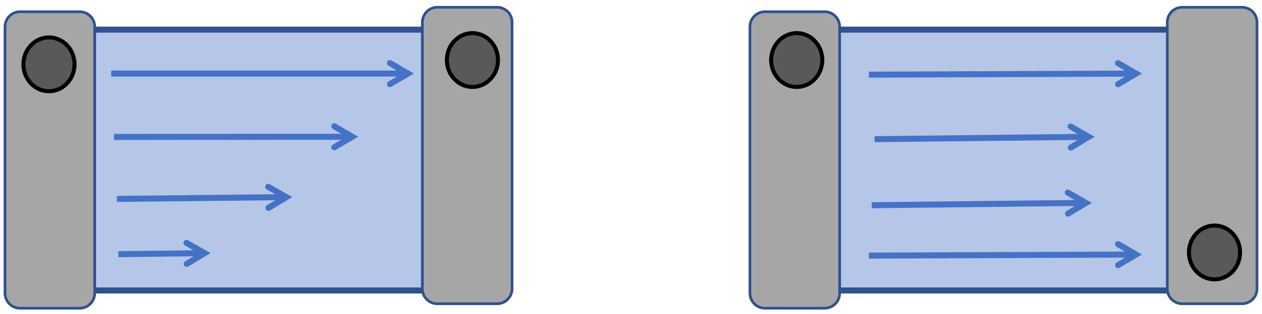

Figure 4-8: Schematic visualization of flow distribution across the radiator core depending on inlet and outlet placement within the end tanks.

The most significant importance of radiator performance regarding the flow pattern can be the so-called single, dual, and triple pass flows. On one side, there is an increase in the pressure drop of the radiator with more passes due to the higher coolant velocity and the bends. However, it also helps to keep the coolant in the desirable turbulent state and lowers the difference in inlet and outlet coolant temperature due to higher velocity. This way, the temperature difference between coolant and ambient air is higher across the core. Therefore, the heat transfer is enhanced. The downside of high-pressure loss can be mitigated with a correct water pump selection. In Figure 4-9, this is represented with slow coolant velocity having blue arrows and faster having red ones.

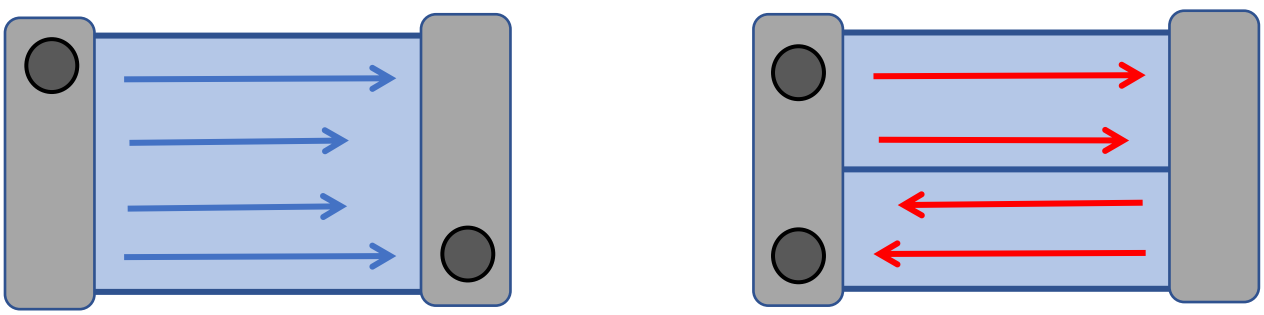

Figure 4-9: Comparison of single pass radiator core with blue arrows representing low coolant velocities and dual pass core with red arrows symbolizing higher velocity.

4.7 Cooling fan

The cooling performance is dependent on the ambient airflow through the radiator. When the car suddenly stops, the loss of ambient air mass flow can lead to engine overheating. To counter that, cars can be equipped with cooling fans. They can be placed in the front or behind the radiator, depending on whether they are designed to produce suction or blow air through it. Usually, axial fans are used, but it depends on the packaging of each vehicle.

The fans can be powered by a mechanical connection to the engine crankshaft. This can provide higher airflow induced by the fan, but the whole system must be placed close to the engine, like in a front-engine vehicle with typical car grills. In these cases, radiators and often condensers for air conditioning and intercooler are located there, so the mechanical fan's high airflow is needed. The downside of this is low control over fan-induced airflow. This can be partly solved by ECU controlled clutch, which regulates fan speed. [14]

The ECU can fully control electrical fans, which can induce airflow for the radiators even when the engine is switched off. They can also be placed where mechanical connection to the crankshaft would be complicated. Figure 4-9 shows the typical electrical fan with a shroud attached to the radiator.

Figure 4-10: Electrical fan with a shroud which helps to distribute the fan-induced airflow across the radiator surface. [14]

4.8 Expansion tank and deaeration circuit

The expansion tank and the deaeration system are supportive parts that keep the coolant inside the cooling circuit and discharge the air bubbles. They also secure a closed cooling circuit in which pressure is controlled by a pressure relief cap located on an upper radiator end tank or on the top of the expansion tank. The expansion tank should be located on the highest point of the cooling system to allow easy deaeration and filling of the cooling fluid inside the system.

When the coolant temperature increases, it starts to expand, and the expansion tank ensures that there is enough space that it does not overflow. It also keeps the system over-pressured to prevent the coolant from boiling. When the pressure is high so it could damage the system the pressure relief cap opens to stabilize it. When the coolant cools down, its volume decreases, creating a vacuum until the pressure relief cap opens to balance it again. Both of these cases can be seen in Figure 4-11, where the upper picture represents coolant expansion, and the lower one stands for the coolant reaching ambient temperature. It is essential to check whether some coolant reserve is left in the expansion tank for the coolant system to work correctly. [14]

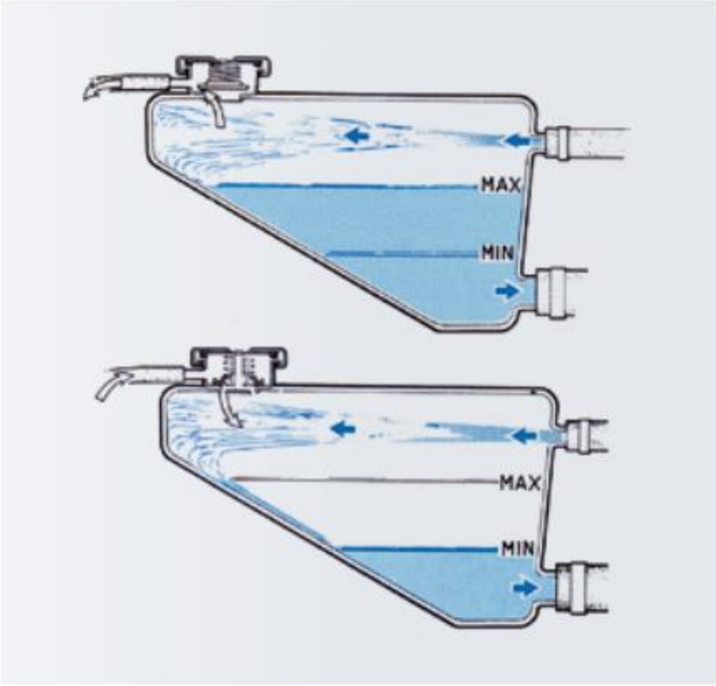

Figure 4-11: Expansion tank with visualized situations when coolant is thermally expanding on the top picture and the opposite on the bottom one. [14]

The deaeration can be done separately on each component, like radiators, but if possible, it is better to connect each location of cooling lines with a local height maximum to the expansion tank, which is the highest point in the entire coolant circuit. Since the air is much lighter than the coolant, it tends to flow to the local height maximums, where it would otherwise cause a decrease in coolant flow and, therefore, loss of cooling capacity.

4.9 Heating, ventilation, and air conditioning

HVAC is a group of devices that ensures comfort in the cabin, helps defog the windscreen and reduces humidity. The elements that are researched in more depth are the heater and the condenser, as both depend on ambient air flow or coolant flow.

4.9.1 Heater

The heater is responsible for increasing the air temperature inside the cabin. It is usually connected to the cooling circuit where it takes the otherwise waste heat. This way, it works similarly to a standard radiator but rather than dissipating heat into the atmosphere, it does it into the air inside the vehicle's passenger compartment. Logically it cannot work when the engine is cold. This can be solved by an electronic heater that does not need a flow of coolant, but on the other hand, it depends on an alternator and batteries for the electric power.

4.9.2 Condenser

Condenser is a part of the HVAC system that needs ambient air mass flow to condense the liquid used in the air conditioning system. Therefore, it occupies a space that could be used for a coolant radiator. Its construction can be described as a radiator with tubes for refrigerant liquid and a finned structure for the ambient air. Since air conditioning is required even when the car is not moving, the ambient airflow must be provided using a cooling fan.

4.10 Engine oil thermal management

Apart from the coolant, there is a need for thermal management of the lubrication system, which is usually the engine oil. It must be kept at operating temperatures high enough to provide proper lubrication of the engine without unnecessary friction and wear and low enough to prevent oil from a thermal breakdown. The system for that shares many similarities with the one for the coolant. There is usually a thermostat, oil pump, valves, and even a radiator as an ambient air-to-engine oil heat exchanger, which can be further equipped with cooling fans.

The main element to describe is responsible for the thermal interconnection of the engine oil with the coolant. It is a liquid-to-liquid heat exchanger with coolant on one side and engine oil on the side. Apart from engine oil, it is often used for gearbox oil as well.

4.10.1 Plate heat exchanger

A plate heat exchanger consists of several heat transfer plates with corrugations stacked on top of each other. These plates are located between so-called frame plates, which offer structural support. All the plates are held together using a brazing technique, preload screws, or a combination of both depending on predetermined operational temperatures, pressures, and used materials. Due to its structure, the plate heat exchanger can be easily scaled by adding more plates.

As illustrated in Figure 4-12, the working principle is based on working fluids passing independently without mixing from one side of the corrugated plate to the other in a counter-current manner. This maintains a larger temperature difference across the whole heat transfer plate which theoretically offers the best cooling capacity. This is important to remember when implementing the heat exchanger into the vehicle because it can be easily connected in a co-current manner, offering less heat transfer. [15]

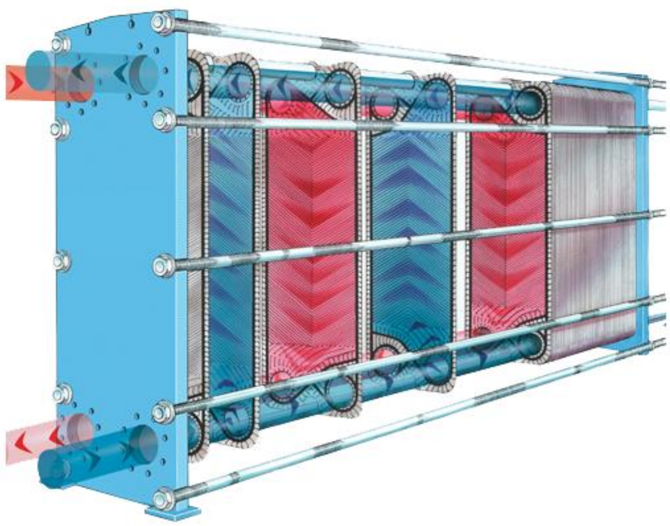

Figure 4-12: Plate heat exchanger with primary working fluid marked red and the secondary blue. Fluids flow in a counter-current manner. [15]

4.10.2 Laminova heat exchanger

This type of heat exchanger consists of a main channel surrounded by smaller ones through which the coolant flows. On the outside is a finned structure which serves as a heat transfer surface for the engine oil encased in an external shell with an inlet and outlet. One of the benefits compared to the plate heat exchanger is lower pressure drop on the coolant side, mainly because of the size of the main channel. Also, fouling resistance for the coolant side should be superior. Overall, thanks to its structure, it is also more resistant to damage. For example, it can be easier to integrate it into an oil tank. Depending on available space, the long oval shape can also be a downside. As it was designed for high flows of coolant compared to the plate heat exchanger placing it in a secondary cooling circuit with low volume flow could lead to lower than intended efficiency. [16]

Regarding the cooling power-to-weight ratio compared to the plate heat exchanger, the Laminova heat exchanger may be slightly worse. On the other hand, the benefits make it certainly a viable choice for some vehicles. In Figure 4-13, several Laminova cores have visible main and secondary coolant channels and fins for cooling the engine oil. The heat exchangers in the picture do not have an external shell to guide the engine oil. [16]

Figure 4-13: Laminova cores with visible main and secondary coolant channels and the finned structure for engine oil. [16]

4.10.3 Shell and tube heat exchanger

Shell and tube heat exchangers are usually linked with large industrial units. With current technology, it is possible to create similar systems on a much smaller scale. The Micro Matrix Heat Exchangers can have tubes as small as 0,3 mm in diameter, leading to a significant size reduction of the whole heat exchanger due to the large surface area. The downside to this compact design is its much higher cost than a standard plate heat exchanger. Compared to the two previously discussed types, this heat exchanger should have the best weight-to-cooling capacity ratio. Usually, these elements are used for aerospace and defence applications, but their use in automotive is also possible. In Figure 4-14, such Micro Matrix Heat Exchanger can be seen. [17]

Figure 4-14: Micromatrix heat exchanger with visible micromatrix tubes and the outer shell. [17]

4.11 Charge air cooling

Even though charge air cooling provided by heat exchangers called intercoolers is almost completely thermally independent of the coolant or engine oil, it still needs ambient air to dissipate the heat. Therefore, the ambient air and place for the intercooler cannot be used by a standard radiator. So, by creating a more efficient intercooler, space can be saved for a bigger radiator or vice versa. In general, there are two ways to make an intercooler: by using ambient air to charge the air heat exchanger or by a system with a liquid to charge air and liquid to the ambient air heat exchanger.

4.11.1 Air to Air intercooler

An Air-to-air intercooler shares many aspects with a coolant radiator. The most apparent distinction is that instead of the coolant tubes with an inner clearance height of around 2 mm, there is an inner tube with a clearance from around 6 to 10 mm with a finned structure inside. This finned structure provides a larger surface for heat transfer and enhances the turbulences, which furthermore help with heat dissipation. Keeping the charge air close to ambient temperature is desirable for proper combustion and maximum power output.

Unlike in the radiator with coolant flow, the charge air has a much higher velocity ensuring that the air is almost always in a turbulent regime. For this reason, the finned structure with its turbulators could cause unnecessary pressure losses, resulting in less air mass flow entering the engine's inlet manifold. Since the pressure loss depends on velocity, the placement of the intercooler end tanks can help reduce it. Below in Figure 4-15 are two types of end tank placement for a core of a similar size. On the left, the charge air has fewer and longer air passages to travel across the core resulting in higher pressure loss. On the right, the opposite setup should provide lower pressure loss while the charge airflow should still be turbulent. [18]

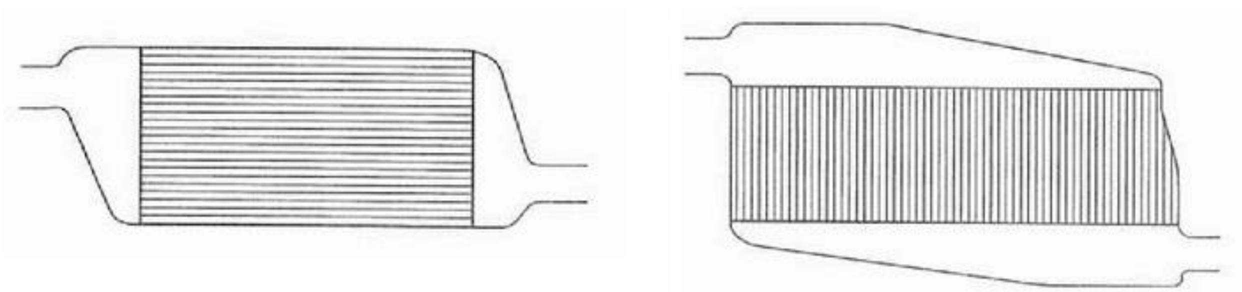

Figure 4-15: Illustration of 2 possible approaches towards end tank placement for an intercooler. [18]

Finding a proper balance between pressure loss flow and heat transfer is a complex task. While the first increases the boost pressure, if losses are reduced, the second reduces the temperature and increases the charge air's density, resulting in more mass flow. The pressure loss must also be aligned with the compressor map for the best efficiency.

Apart from Tube and Fin design already discussed in the radiator section, there is a Bar and Plate intercooler. The thin brazed extruded tubes used in Tube and Fin types are replaced with welded bars and plates. The finned structure remains the same.

This allows for higher boost pressure of the charge air without the risk of damage and leakages. Also, it is more resistant to external damage, for example, from stones impacting the core during a rally race. But on the other hand, it is much heavier, so in applications where durability is not the primary concern, it is better to use Tube and Fin design. [19]

Figure 4-16 shows the Bar and Plate design on the left and the Tube and Fin on the right. The fact that each type has a different inner fin style can be ignored since this is independent of the main construction approach.

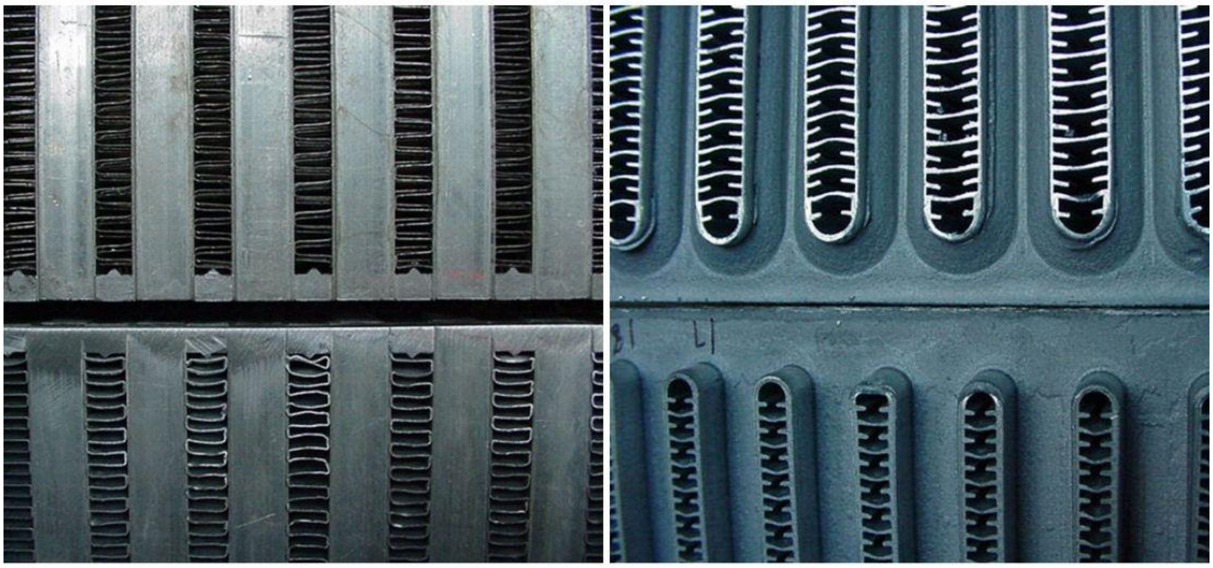

Figure 4-16: Visual comparison of the charge air side of Bar and Plate intercooler core on the left with Tube and Fin design on the right. [19]

4.11.2 Water-to-air intercooler

Creating functional water to charge the air intercooler would need more components than its air-to-air counterpart. For the charge air side, a water-to-air heat exchanger would be needed. It could be made as a reverse radiator, having a Laminova design with charge air in place of engine oil, or it could utilise microtubes technology. It could be implemented directly into the intake manifold reducing the required space and possible turbo lag.

For the water, in case of cold temperatures, the same coolant mixture engine is cooled with could be used. There is a need for a separate cooling circuit with a water pump and a classic radiator to dissipate the heat into the atmosphere. Only the expansion tank could be theoretically shared with the engine coolant system operating at higher temperatures. All of it together requires space, increases weight and would be more expensive. Due to its complexity, there is also a rising danger of some parts malfunctioning. However, in many cases, the benefits overcome the downsides. The most important benefit lies in the thermal conductivity difference between air and water, which can be more than 15 times higher in favour of water. This can lead to space and weight savings but, most importantly, to shorter passages or less dense fins needed for the charge air side, reducing the pressure loss. [20]

5. Scenarios

After the research of various cooling system elements, hypothetical vehicles can be discussed regarding their function under various scenarios. Each of these scenarios presents a substantial challenge to cooling and engine lubrication and, to a limited degree, to the HVAC system. This can be considered a transition from the research part of the thesis to the part with the Bohema cooling scheme development.

For the cold environment scenario temperature will be set to -20°C, and for the warm environment, it will be 50°C.

All the vehicles discussed will have a spark-ignited turbocharged combustion engine for better comparison.

The first will be a standard passenger car with front-mounted ICE, which has its cooling system equipped with primarily mechanical elements like a coolant pump and fan, thermostat and heater. Its engine oil will be cooled by ambient air to the oil radiator, and the air conditioning will not be present. Therefore, it can be viewed as an old vehicle from the Mid-20th century. It will be called an "old car" and analysed first.

Next will be a modern passenger vehicle, further referred to as a "modern car", equipped with electronic elements to control its cooling system, designed with emission mitigation and fuel efficiency in mind. Also, the HVAC for better comfort will be present.

Last will be a racetrack-only vehicle resembling the ones from competitions like an F1, which do not have parts like HVAC, thermostat, cooling fans or electrical pumps. It will be called a "race car" and analysed as last.

5.1 Starting the engine and warm-up

This phase can be viewed as a period from starting the engine until the working fluids reach operating temperatures.

Cold environment

The old car will take longer to warm up the engine oil since the only heat source is the ICE with no designated liquid-to-liquid heat exchanger. The coolant, a mixture of water and glycol resistant to freezing, will reach the operating temperature before the oil because of its better heat conduction properties and engine geometry. The thermostat for both fluids will be closed until the end of this phase. It is important not to run this vehicle until the engine with both working fluids warms up. Otherwise, it could suffer from unnecessary engine wear, fuel consumption and emissions. The heater turned on by a mechanical valve will start warming up the cabin as the coolant increases the temperature at the cost of prolonging the warming-up process due to additional heat dissipation.

The modern car with a heat exchanger for both engine oil and coolant and possibly even electronic devices to heat the working fluids will take a shorter time to warm up than the old car. The coolant must be resistant to freezing. Given enough battery power, an electric heater will allow for independent cabin thermal regulation without compromising the warm-up process.

The race car with coolant consisting of glycol can theoretically work, but since it has no thermostat reaching the operating temperatures, it would take a significant time if the engine can be started in the first place. It is due to the engine being designed for race conditions only. It could be warmed up externally before cranking the engine, which should solve the problem. If the coolant is based on pure water, keeping it at freezing temperatures will cause a rupture in coolant lines or radiator since water would turn into ice.

Hot environment

With high temperatures, it will take only a short time until the coolant and engine oil reaches operating temperature and the old car is ready to drive. Since the air conditioning is not present in the old car, the passenger can open only windows and air vents.

A modern car would behave similarly to the old car with only the major exception of working air conditioning.

Race car would behave like an old car, but it could still benefit from the external warming up before cranking the engine.

5.2 Maximum engine load

This simulates a vehicle driven on a circuit for a prolonged time with the engines operating under full load whenever the traction allows.

The cold environment scenario will not be discussed in detail since it presents lower requirements for the cooling system. The modern car should be able to control the engine temperature better than the old car but with no real issues facing both vehicles. Race cars only problem would be the discomfort for the driver due to the lack of a heater.

Hot environment

Since most passenger cars are not made for these conditions, it would be only a matter of time before either driver slows down or the coolant reaches temperatures high enough and starts boiling. In that case, eventually, the pressure relief valve would open to prevent overpressure damage. It could still lead to engine failure with potential damage due to high thermal stress. Engine oil would start degrading due to high temperatures, which could decrease lubrication and again, potential engine damage in worst-case scenarios could occur. Opening both the heater valve and window could help to prolong the time until failure at the cost of discomfort for the driver. The intercooler may not be able to cool down the air enough so that the engine could start knocking, resulting in loss of power and more potential damage.

A modern car would share the same fate as the old car, but it may not be that impacting since it could be prevented by ECU, which would adjust the engine power output. The air conditioning with its devices like a compressor would decrease the engine power output by increasing the mechanical losses on the drive belt. Engine oil temperature could be managed better by the liquid-to-liquid heat exchanger. The intercooler would probably not be able to cool down the charged air enough, but the ECU would prevent the knocking by adjusting the combustion process, resulting in a lower power output.

Race cars are made to sustain these harsh conditions with a properly designed cooling system. But since they do not have control elements like a modern car, they are less resilient if critically high temperatures are reached. This could result in more severe damage to the engine and cooling system.

5.3 Cooling down

This scenario should be understood as continuing the previous one after the engine and working fluids reach the maximum possible temperatures for safe operation and the vehicle suddenly stops. It means the vehicle has zero velocity, and the engine has low speed in its idle state. It can be presented by an inexperienced driver on a racetrack who stops the car without doing a cool-down lap. Unlike the maximum engine load on a race track, it cannot be solved by increasing coolant volume flow, radiator size or changing the aerodynamic package for more ambient air mass flow.

Like the previous scenario, the cold environment condition is not worth discussing since it presents a lesser challenge without the need for any new functionality of the cooling scheme.

Hot environment

The old car is not moving, and the engine is idle means that the water and oil pump would be able to force the coolant to circulate, but its volume flow would be very low. Another problem would come from the ambient air mass flow. A mechanical fan connected to the crankshaft would induce airflow, but it would be far weaker than if the car was moving. Both issues would result in reduced heat dissipation in radiators. If the heat rejection from the engine block and cylinder heads into the coolant could not be balanced by the heat rejection in the radiators into the atmosphere, the coolant already at the peak temperature could start to boil, leading to potential damage. It could be best to turn off the engine entirely in that case. Engine oil would start to degrade, but since the engine is no longer producing heat as it slowly cools down, the degradation would be a problem. The charge air would not be needed with the engine idle or turned off.

For the modern car, this should not be a problem. The working fluid would flow through the system with an electric pump while the electric fan would provide the radiators with ambient air mass flow. The coolant in the heat exchanger will cool down engine oil. The air conditioning should work without any problem. The engine could be turned off to reduce heat generation even further. The only issue would arise if the batteries were depleted. Then, it would depend on the alternator powered by the idle engine and its ability to run all the electricity-dependent devices.

Race cars should be able to sustain these conditions since the engine and all the cooling system elements are generally built to work in higher temperatures than ordinary cars. Moreover, since the race car engine is made to be as light as possible, the heat accumulated in the engine structure would be lower than in previous cars meaning there would not be a substantial amount of heat to dissipate. Ideally, a team with external fans would cool down the race car.

6. Research conclusion

It is essential for cooling scheme development to analyze how Bohema should function concerning the hypothetical scenarios discussed before.

Bohema is designed to behave as a race car on track, but unlike the race car, it can be driven by an inexperienced driver without a supporting team to provide external cooling or heating. The driver's comfort in the cabin is important, but not to the degree that the heater should heat the cabin before the driver starts the engine. It is expected that it will be parked in a garage and not outside a house like an ordinary passenger car. Since the performance and weight are of great importance, relying on heavy batteries and maybe unnecessarily large alternator for electronic thermal management devices should be minimised. Finally, emissions control and fuel consumption are necessary to keep in check since the vehicle does need to pass homologations with the ever-increasing requirements.

In other words, Bohema needs a cooling capacity like a race car with a functional HVAC and electrical components for a reliable cooling down process. Keeping the number of electronic elements at a minimum is desirable to reduce the reliability on the battery pack and alternator and the subsequent thermal control complexity.

Given the scenarios, constraints and goals mentioned at the beginning of the thesis, the following parts should be in the Bohema.

The radiators and intercooler should be as large as the package allows. The electric pump for the coolant and electric fans should successfully overcome the cooling down issues. Coolant should be based on a water and glycol mixture for the car to drive and stay in a cold environment. A thermostat can stay purely mechanical, and a heater can depend on heat flux via coolant from the engine. For oil thermal management, the liquid-to-liquid heat exchanger would be the best option, but due to uncertain cooling capacity, it would be better to have oil-to-ambient air radiators as support. Intercoolers should be directly cooled by ambient air, and since air conditioning is required, there must be some space left for a condenser.

7. Calculations of heat transfer

Before describing the cooling scheme, it is crucial to present heat transfer calculations for the radiators. It was created to help with fundamental decisions like whether to place radiators in parallel or series and if they should work as single, dual, or triple flows. The calculations are simplified since the thesis aims to obtain the main design parameters and not get as precise results as possible. It will be explained how the mathematical model has to be adjusted to calculate the cooling capacity of the air-to-air intercooler. This can be viewed as the beginning of the analytical part of the thesis.

The calculation will focus on forced convection since the coolant is circulated by pumps, and ambient air mass flow depends on vehicle speed and fans. Free convection, coolant boiling, radiation, and conduction to other vehicle parts will not be considered.

7.1 Input parameters

7.1.1 Working fluids properties

Starting with the coolant, the critical property is the composition of the fluid itself. The model can, for example, evaluate the potential benefit of cooling performance if a water-based coolant is used instead of a mixture of water with glycol.

For the coolant and ambient air, the properties which are necessary for calculation are:

- Density – ρ
- Dynamic viscosity – μ
- Specific heat capacity – c
- Thermal conductivity – k
- Inlet Temperature – T_{in}

Exact values can be obtained from datasheets, and their dependency on temperature should be kept in mind. Specific heat capacity for both fluids must be taken as isochoric since the coolant is in a closed system, and ambient air passing through the radiator does not change the volume along its path. Since the temperatures of both fluids decrease along the flow length in an ideal case, the values of physical properties mentioned above should correspond to the mean temperature. This would require obtaining outlet temperatures which would lead to the iterations. Thermal conductivity will be needed for the aluminium radiator as well. In this case, it will be marked as λ and not k.

For further simplification to remove the need for iterations, the values of said parameters can be determined based on only the inlet temperature. The temperature of both fluids changes in a range which almost does not influence output cooling capacity. Therefore, this step of simplification is possible. The same can be said about the omission of pressure changes.

7.1.2 Flow rates of working fluids

The most crucial variable regarding the influence on output cooling capacity is the flow rate of working fluids.

- Mass flow of ambient air – $\dot{m}$
- Volume flow of coolant – $\dot{V}$

Starting with the mass flow, determining its value is a costly and time-demanding process. Due to the complexity of the Bohema aerodynamic package, the mass flow must be obtained from CFD simulations of the whole or symmetrical vehicle model in a virtual wind tunnel. Here the effect of sidepod duct geometry and fan-induced airflow can be evaluated. As a radiator representation for the CFD, the characteristics of pressure difference based on the ambient air mass flow are needed. It can be provided by the radiator core manufacturer or from core measurements. Another way to obtain the mass flow is by measuring the vehicle in a wind tunnel or racetrack. However, this requires an already-made cooling solution, making it rather one of the means of validation.

The volume flow of a coolant depends on the used pumps and the geometry of coolant lines, including the engine. Therefore, its value should be measured.

7.1.3 Radiator core construction

The three geometrical parameters listed below mainly depend on the available space for the radiator inside the vehicle. They serve as radiator geometrical representations within the calculation.

- Radiator flow length – R_{fl}
- Radiator thickness – R_t
- Number of passes – n_X

Flow length is the distance from the inlet to the outlet end tank, and as its name states, it is the parameter for the flow length of a coolant. A more detailed explanation with visual representation can be found in the 4.6.1 segment of the thesis. Thickness is the distance from the inlet to the outlet face for the ambient air, which makes it a flow length for the ambient air.

The coolant tubes have the following parameters:

- Tube inner height – T_{ih}
- Tube inner width – T_{iw}
- Tube thickness – δ
- Number of tubes – n_T

The tubes are rectangular with cross-section widths usually slightly less than the core thickness and inner heights of around 1-2 mm.

The turbulated fins are the most complicated element of a radiator due to their complex geometry. The model uses the below-mentioned parameters.

- Fin height – Fh
- Fin width – Fw
- Fin density – $Fpul$
- Number of Fin rows – n_F
- Fin efficiency – η

Figure 7-1: Representation of fin density within one fin row between 2 coolant tubes. The coolant tube surface is grey, and the fins are blue.

Fin height is the distance between coolant tubes. Summarized with the tube height, the stack height can be calculated. It is the third and last major radiator dimension, along with the radiator flow length and radiator thickness. Fins density is the number of fins per unit length, as seen in Figure 7-1. Fin efficiency accounts for the fact that further from the coolant tube, the temperature of the fin and, therefore, its heat transfer decreases. It is the ratio of the heat transferred by a fin divided by the heat that the fin surface would have dissipated if it had the coolant tube temperature. Since it is dependent on output parameters, its determination would require iterations. The core manufacturer can provide its characteristics.

Another simplification is done by not considering parameters like fin thickness and fin louvre geometry. Louvres are small flaps which induce turbulences in the ambient airflow.

7.2 Heat Transmission Through a Tube Wall

First, the combined heat resistance R_A has to be found. It is reciprocal to the overall heat transfer coefficient k_R and the reference surface A. The one-dimensional equation for heat transmission through a tube wall (1) is used for this step.

$$R_A = \frac{1}{k_A A} = \frac{1}{\alpha_c A_c} + \frac{\delta}{\lambda A_m} + \frac{1}{\alpha_a A_a} \tag{1}$$

The first element represents the convective heat resistance of the coolant flowing through the tubes. The second element stands for conductive resistance in the metal, therefore, in the radiator walls, and the last resistance represents once more convective heat resistance on the ambient air side.

7.2.1 Heat transmission surface

The heat transmission surface for the coolant depends on the geometry and number of coolant tubes per pass of the radiator. It is calculated using the equation (2).

$$A_c = \frac{n_T}{n_X} \cdot 2 \cdot R_{fl} \cdot (T_{ih} + T_{iw}) \tag{2}$$

For the second element of equation (1), I must find the logarithmic mean area A_m between the outer and inner tube surface. In eqn. (2) I have already calculated the overall inner tube surface, so the first thing to do is calculate the same for the outer surface A_{cext}.

$$A_{cext} = \frac{n_T}{n_X} \cdot 2 \cdot R_{fl} \cdot (T_{ih} + T_{iw} + 4 \cdot \delta) \tag{3}$$

Now the logarithmic mean area can be obtained with equation (4). This will result in a single value that is between A_c and A_{cext} as if the tubes were circular.

$$A_m = \frac{A_{cext} - A_c}{\ln(\frac{A_{cext}}{A_c})} \tag{4}$$

The contact surface between the ambient air and radiator consists of a tube and fin surface. The fin surface is multiplied by fin efficiency.

$$A_a = \frac{n_F}{n_X} \cdot \frac{R_t}{\frac{1}{F_{pul}}} \cdot 2 \cdot R_t (F_w \cdot \eta + \frac{1}{F_{pul}}) \tag{5}$$

The fin efficiency can possibly be omitted since its value is usually close to 1.

7.2.2 Heat transfer coefficient

The hydraulic diameter D must be determined to calculate the heat transfer coefficient. It allows work with the rectangular geometries as if they were circular. This has to be done for both the coolant tube and the rectangular radiator slit constrained between two fins and two coolant tubes.

$$D_{coolant} = \frac{2 \cdot T_{ih} \cdot T_{iw}}{T_{ih} \cdot T_{iw}} \tag{6}$$

$$D_{amb.air} = \frac{2 \cdot \frac{1}{F_{pul}} \cdot F_h}{\frac{1}{F_{pul}} + F_h} \tag{7}$$

Now using the equations (6) or (7), the value of Reynolds number for each fluid must be found. The equations are identical except for the lower indexes therefore, only 1 equation is shown.

$$Re = \frac{\rho \cdot \frac{\dot{V}}{T_{ih} \cdot T_{iw} \cdot \frac{n_T}{n_X}} \cdot D}{\mu} \tag{8}$$

Below Reynolds number 2300, the coolant is considered as laminar and above that as turbulent, omitting the transitional region due to its complicated behaviour. However, the ambient air is considered turbulent even for Reynolds numbers below 2300. It is because radiator fins have turbulator specifically designed to keep the air in a turbulent state at low velocities.

In the following equations, when proving the validity range of Re, the upper boundary for the turbulent regime will not be written since its value is beyond that which can occur in the considered radiators.

Using the Reynolds number from equation (8), the Nusselt number can be approximately calculated for hydrodynamically developed laminar flow according to Baehr and Stephan, as stated in the book VDI Heat Atlas. [21]

$$Nu = \frac{3.657}{\tanh\left(2.264 \cdot X^{\frac{1}{3}} + 1.7 \cdot X^{2/3}\right)} + \frac{0.0499}{X} tanhX \tag{9}$$

According to VDI Heat Atlas, this equation is valid for laminar flow up to Re 2300. The dimensionless X can be calculated using equation (10). [21]

$$X = \frac{R_{fl}}{D \cdot Re \cdot Pr} \tag{10}$$

The Prandtl number can be taken from tables, coolant technical documentation or calculated using equation (11).

$$Pr = \frac{c \cdot \mu}{k} \tag{11}$$

The Dittus–Boelter equation for cooling (12) can be used for the turbulent region. Nevertheless, as stated in the book Fundamentals of Heat and Mass Transfer, this simpler equation may cause errors as large as 25% with validity for Re ≥10 000. For these reasons, it could be better to use the correlation for smooth tubes provided by Gnielinski (13), which included the transitional region and should yield an error lower than 10%. As the authors note in the book for the equation (13), if used with Re ≤10 000, the convection factor could be overpredicted even though it is stated that the equation is valid for Re ≥ 3000. [22]

$$Nu = 0.023 \cdot Re^{4/5} \cdot Pr^{0.3} \tag{12}$$

$$Nu = \frac{(f/8) \cdot (Re - 1000) \cdot Pr}{1 + 12.7 \cdot (f/8)^{0.5} \cdot (Pr^{\frac{2}{3}} - 1)} \tag{13}$$

However, the eqn. (13) is not ideal for calculating ambient airflow in the radiator since it should be turbulent, but its Re is not large enough. So after consultation and preliminary calculation, another eqn. for turbulent flow through the pipes was selected. It is based on Petukhov's equation modified by Gnielinsky, as stated in the book VDI Heat Atlas. It is valid from Re ≥10 000, just as the equations above. [21]

$$Nu = \frac{(f/8) \cdot Re \cdot Pr}{1 + 12.7 \cdot (f/8)^{0.5} \cdot (Pr^{\frac{2}{3}} - 1)} \cdot \left[1 + (\frac{D}{L})^{2/3}\right] \tag{14}$$

The L in equation (14) stands for either radiator flow length or radiator thickness, depending on if I want to calculate the coolant or ambient air.

In equations (13) and (14) the f is a friction factor which can be obtained from the Moody chart or calculated using equation (15). [21]

$$f = (0.78 \cdot \ln(Re) - 1.5)^{-2} \tag{15}$$

Now the convective heat transfer coefficient α from the definition of the Nusselt number for both the ambient air and the coolant can be calculated. Equations (7) and (14) are needed for the ambient air. For the coolant, it is eqn. (7) and (14) or (9), depending on if the coolant is in a laminar or turbulent regime.

$$\alpha = \frac{Nu \cdot k}{D} \tag{16}$$

After that, the combined heat resistance R_A from equation (1) can finally be calculated.

7.3 NTU Method and cooling capacity

The straightforward approach to determine the cooling capacity of a heat exchanger would be to use the logarithmic mean temperature difference however, this would require knowing both the inlet and outlet temperatures. Therefore, another approach known as NTU Method is required. [22]

First, the heat capacity rates of both fluids have to be found.

$$\dot{W}_{coolant} = c_{coolant} \cdot \dot{V} \cdot \rho_{coolant} \tag{17}$$

$$\dot{W}_{amb.\ air} = c_{amb.\ air} \cdot \dot{m} \tag{18}$$

Now, the heat capacity rate ratios for both fluids can be calculated.

$$R_1 = \frac{\dot{W}_{coolant}}{\dot{W}_{amb.\ air}} \tag{19}$$

$$R_2 = \frac{\dot{W}_{amb.\ air}}{\dot{W}_{coolant}} \tag{20}$$

And the dimensionless number of transfer units for both streams of fluids.

$$NTU_1 = \frac{k_A A}{\dot{W}_{coolant}} \tag{21}$$

$$NTU_2 = \frac{k_A A}{\dot{W}_{amb.\ air}} \tag{22}$$

Implementing the dimensionless correction factor F with the approximation equation (23) relates the cross-flow radiator design to the pure counter-current heat exchanger. This allows the calculation of dimensionless temperature changes and the actual outlet temperatures. Due to the construction of radiators concerning the thesis, the following values for coefficients a, b, c and d from the book VDI Heat Atlas must be used. The coefficients vary for different flow arrangements. The values for pure cross-flow heat exchangers are used since all of the considered radiators have more than 20 coolant tube rows. If the radiators had, for example, only ten coolant tube rows, different values would be used. Nevertheless, it is important to keep in mind that those different values would not change the output cooling capacity by more than 0,1 %. [21]

a = 0.433; b = 1.6; c= 0.267; d = 0.5

$$F = \frac{1}{(1 + a \cdot R^{db} \cdot NTU^{b})^{-c}} \tag{23}$$

The dimensionless temperature change can be calculated for both fluids using Eqn. (24), initially valid for a pure counter-current heat exchanger, is changed by implementing the correction factor from equation (23). Additionally, the heat capacity ratio from Eqn. (19) or (20) and the number of transferred units from eqn. (21) or (22) are needed. Depending on whether the aim is to obtain coolant or ambient air results. [21]

$$P = \frac{1 - e^{[(R-1)\cdot NTU \cdot F]}}{1 - R \cdot e^{[(R-1)\cdot NTU \cdot F]}} \tag{24}$$

From the definition of dimensionless temperature change in 2 streams from equation (25), I can calculate the outlet temperature for the coolant (26). The same can be done for ambient air.

$$P_{coolant} = \frac{T_{coolant-in} - T_{coolant-out}}{T_{coolant-in} - T_{amb.air-in}} \tag{25}$$

$$T_{coolant-out} = T_{coolant-in} - P_{coolant} \cdot (T_{coolant-in} - T_{amb.air-in}) \tag{26}$$

Having the temperature change, the cooling capacity of the radiator or, in case of multiple passes for each pass with the equation (27) can be determined. The results are equal for the coolant or ambient air since the heat as an energy cannot be created nor destroyed.

$$\dot{Q} = \dot{V} \cdot \rho_{coolant} \cdot c_{coolant} \cdot (T_{coolant-in} - T_{coolant-out}) \tag{27}$$

The convenience of this analytical model is that if calculation of the second pass of a dual-pass radiator is required, the coolant outlet temperature from equation (26) from the first pass can be used as an inlet temperature for the second pass with both passes being geometrically identical. Consideration must be taken that there will be additional minor errors if the coolant properties are not changed because of different temperatures. To achieve better accuracy, on the other hand, each radiator or even each radiator pass can be divided into several smaller units, each with different properties based on different temperatures. The practical feasibility of this refinement is questionable when building this model in software like Microsoft Excel or free-to-use Google Sheets, which was the case for the thesis. On the other hand, in more expensive MATLAB, it could be done without much problem.

7.4 Air-to-air intercooler model adjustments

The intercooler calculations for the ambient air side remain the same as for the radiator. The charge air side can be presumed as a coolant tube with internal fins. Therefore, to calculate the surface for the heat exchange of the charge air, similar equations as for the ambient air can be used. Using more than one pass for the intercooler would be unwise due to the additional pressure loss. However, due to the larger expected temperature change of the charge air, refining the intercooler into several units along the flow length could be necessary if more accurate results were needed.

7.5 The turbulent regime's importance

This segment was included to describe the benefit of a turbulent regime in especially coolant tubes of the radiators but also concerning the ambient and charge air. The higher value results for the Nusselt number can be seen from the equations for laminar and turbulent regimes. However, it is much easier to present the benefit more visually.

The main reason why the turbulent regime is desirable can be visualized in Figure 7-2. From a heat transfer perspective, the important property of a turbulent regime is the radial mixing of the fluid which is not present in a laminar regime. This allows for more even temperature distribution across the tube cross-section, where the difference between turbulent and laminar regimes could be partially correlated to the velocity distribution. The temperature of the fluid near the wall is crucial for the heat exchange since there the heat is transferred into the wall and further into the ambient air. Moreover, due to the much steeper velocity gradient of the turbulent regime near the wall, the coolant tube surface is more resistant to fouling which is a slow but gradual process forming an insulation layer from various sediments. [23]

Nevertheless, it needs to be kept in mind that the higher the Reynolds number, the higher the pressure losses, which means that it is desirable to have a turbulent regime only where it can be utilised for heat transfer. Therefore, it should be laminar in the radiator end tanks or coolant tubes and pipes outside the radiator since there it cannot be cooled by the passing ambient air. Also, the surfaces outside the radiator coolant tubes should be as smooth as possible to decrease pressure losses.

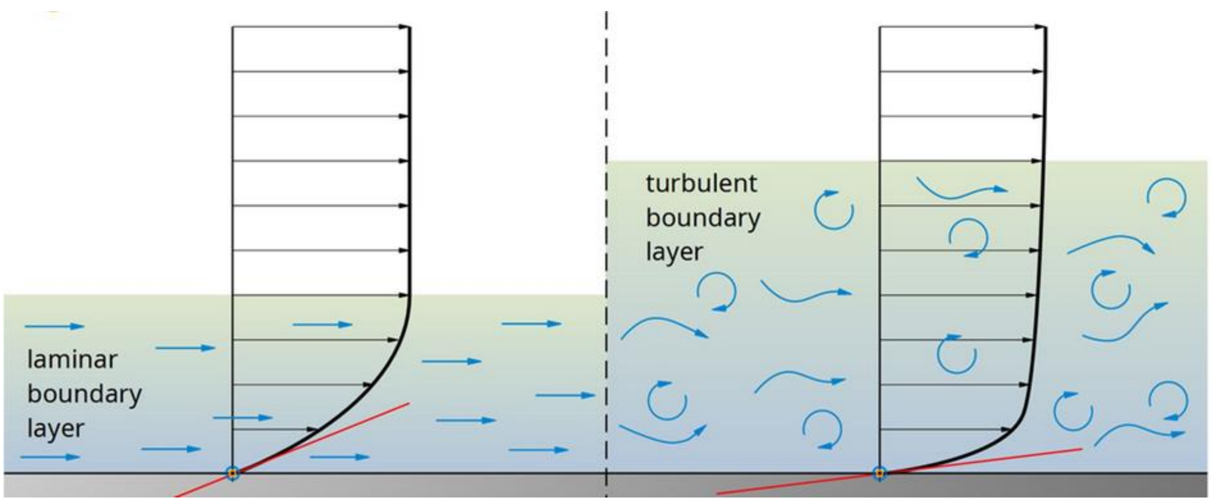

Figure 7-2: Visualization of difference between laminar and turbulent boundary layer from velocity perspective. [23]

7.6 Calculation conclusion

The results of the said analytical model for heat exchange will be later discussed in the cooling system development segment. Using this model, the cooling capacity of each radiator, just as of the whole cooling system, can be predicted.

The predictions are only as precise as the input. Some based on CAD or real-life geometry are easier to determine and obtain compared to the coolant volume flow and ambient or charge air mass flows.

It is obvious that by using the empirical correlations, the mathematical model cannot be precisely equal to the data that could be measured once the system is manufactured and measured. Introducing additional coefficients correlated to the measured data could increase the precision of the model. It could then help with further development stages of the cooling system if needed.

8. Cooling system scheme

Here begins the second part of the thesis. It contains the decisions made for the cooling system development using the calculation model from Chapter 7, whenever it was applicable.

The diagram in Figure 8-1 shows one of the final cooling schemes that has been developed. The core of this scheme is based on Figure 4-1, with added and changed radiators for coolant and engine oil. In addition, intercoolers, oil pump and condenser are other new elements. For simplicity, the deaeration lines and expansion tank are not shown.

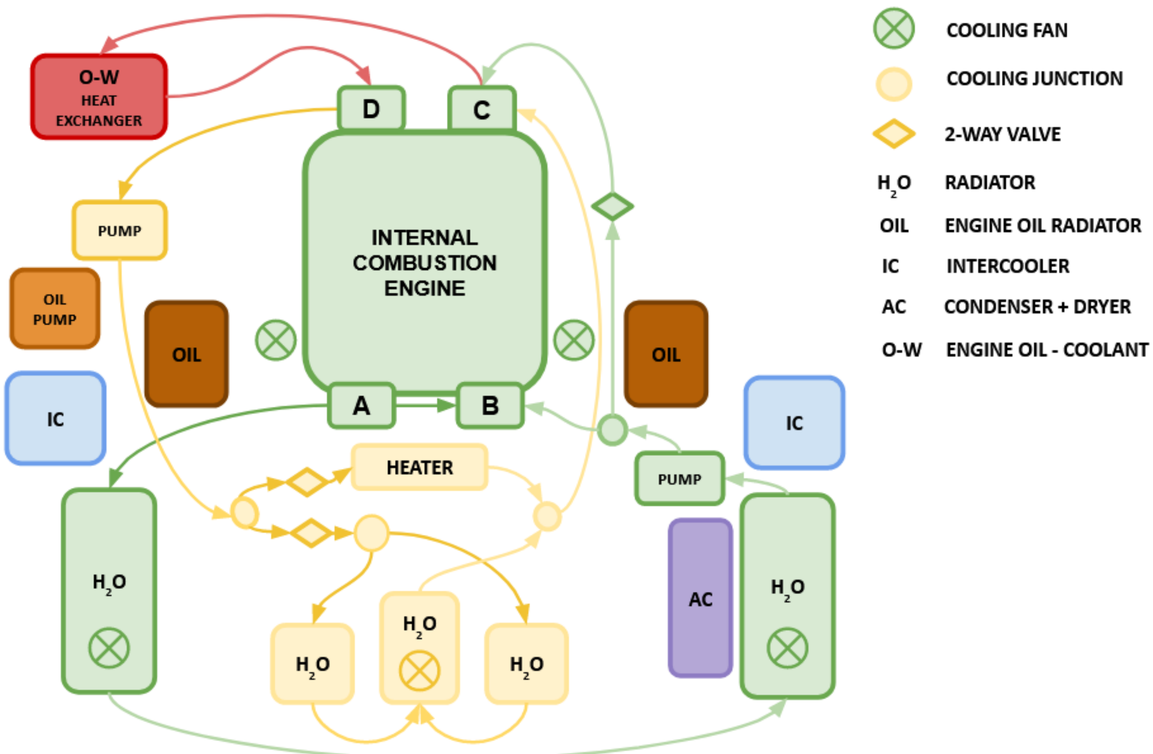

Figure 8-1: Cooling scheme representation.

The function of yellow, green, and red circuits in Figure 8-1 is similar to that in Part 4 - Cooling system elements of the thesis. There are new radiators and additional electronic valves to better control the yellow circuit. The first new element marked with AC is the condenser with a drier which is a part of the air conditioning unit. IC stands for air-to-air intercoolers, and OIL represents the engine oil radiators. The oil lines are not shown in the scheme for simplicity. The engine oil in the heat exchanger is circulated with a high-pressure mechanical oil pump which is a part of the engine. An oil pump is an additional low-pressure electronic pump responsible for circulating the fluid inside the oil radiators connected to the oil tank.

Part 5 of the thesis showed that for a vehicle, there are three challenging scenarios from the perspective of a cooling system: Starting the engine and warm-up phase in a cold environment, maximum engine load and subsequent cool-down phase in a hot environment.

Starting the engine and warm-up in a cold environment

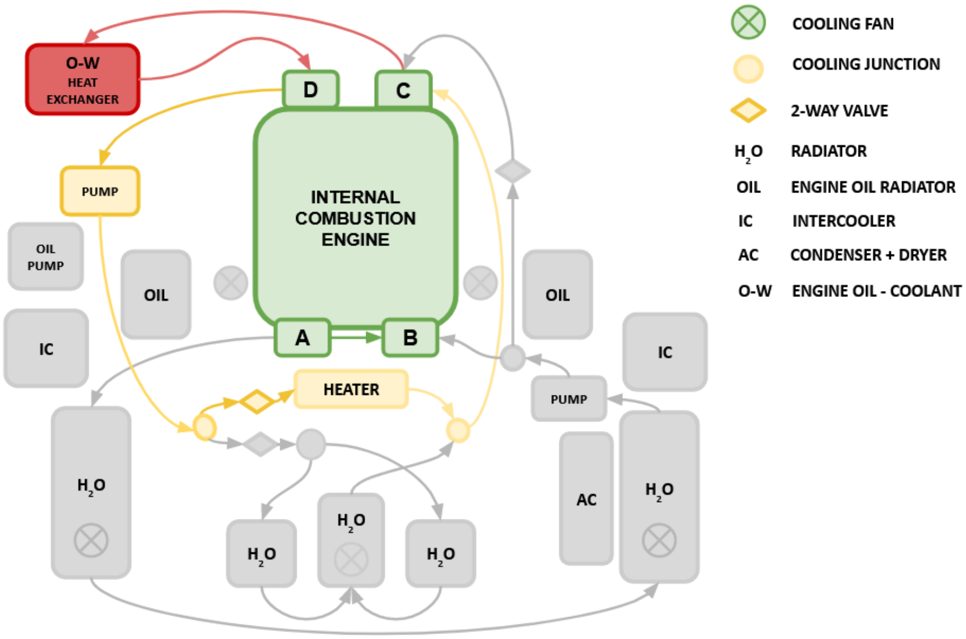

Figure 8-2: Cooling scheme in a warm-up phase.

The grey elements in Figure 8-2 visualize the unused elements which are either not operating or, like the intercoolers, their operation is insignificant. During the warm-up phase, the coolant with anti-freezing properties circulates within the engine with the primary thermostat valve closed, preventing the coolant from flowing into the primary radiators. For passenger bay comfort, the small electric pump in the yellow circuit forces the heated coolant from the engine into the heater. The 2-way valve in a yellow circuit prevents the three radiators from dissipating additional heat. The engine oil is heated in the heat exchanger by the passing coolant.

Maximum engine load in a hot environment

The air conditioning should be switched off for maximum cooling capacity and engine power output. The heater is in a hot environment and switched off using a 2-way valve. Therefore all the coolant, with the help of the electric pump in the yellow circuit, flows through the additional radiators, where it dissipates heat. The heat exchanger cools down the engine oil, and the oil radiators are supported by the engine oil pump. Intercoolers dissipate heat from the compressed ambient air. The main thermostat valve is fully opened, and the green circuit 2-way valve is closed. Therefore, engine recirculation and coolant flow via the thermostat bypass line is not possible. The electric pump in the green circuit ensures coolant flow whenever the pilot has to slow down, and the mechanical pump is not sufficient. The cooling fans mounted from the inboard side of the oil radiators near the ICE in Figure 8-1 are switched on to ventilate the engine bay. The radiator fans can be switched off to save electric power or kept running for additional ambient airflow.

Cooling down in a hot environment

The air conditioning unit is working for comfort in the passenger bay. The oil radiators and heat exchangers are cooling down the engine oil. The engine bay is ventilated with cooling fans. The heater part of the yellow circuit is closed, and the radiator with the cooling fan is dissipating heat. The green circuit with radiators, fans and an electric pump is responsible for most of the cooling capacity in this scenario. The thermostat bypass circuit ensures that the coolant flow into the engine even if the thermostat is closed. It could theoretically close due to the low flow rate of cold coolant flow from radiators while the engine body still has a high temperature. This condition should not occur during higher than idle engine speeds. Therefore, the bypass circuit can be considered a safety measure for the cooling down process.

8.1 Modifications

8.1.1 Simplification

If the cooling capacity of the radiators proves to be more than sufficient during the testing, the additional radiators of the yellow cooling circuit can be removed. The same goes for the oil radiator and the electrical oil pump. The cooling fans on the oil radiators would stay since their role is to provide the engine bay with ambient airflow drawn from the sidepod. The oil radiators could be replaced with louvres to regulate the airflow into the engine bay, which, otherwise unrestricted, would partially reduce the airflow for the radiators and intercoolers. Figure 8-3 shows this simplification of the former cooling scheme.

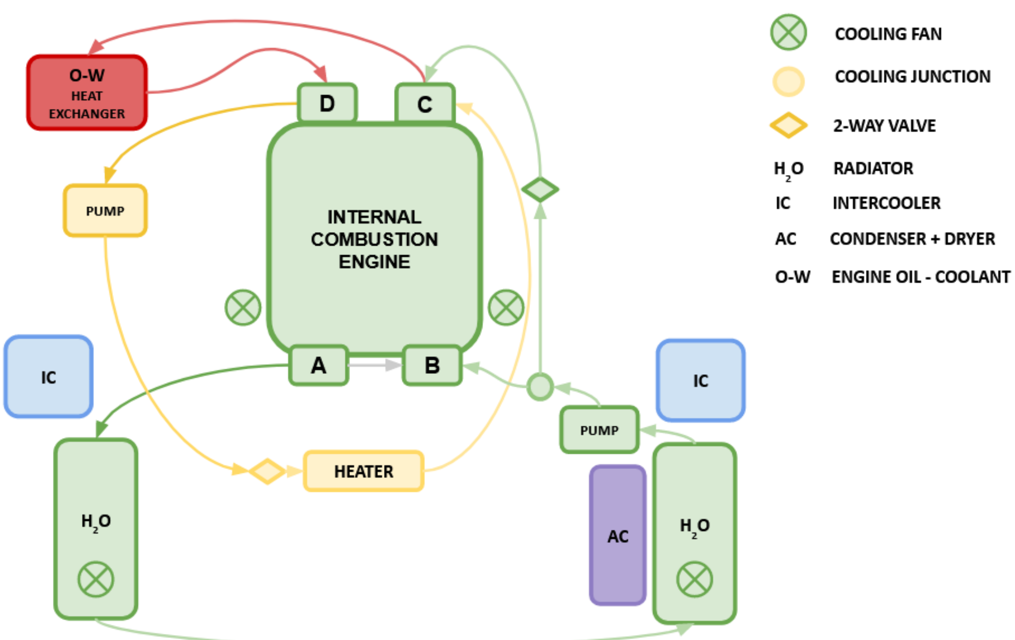

Figure 8-3: Simplified cooling system.

8.1.2 Insufficient heat exchanger cooling capacity

One logical concern of the system in Figure 8-1 is that the hot coolant from the engine will not be able to cool down the engine oil in a heat exchanger. The thermostat bypass circuit can be rerouted into the heat exchanger to use the colder coolant from the primary radiators. Not to lose the benefit of the heat exchanger to heat the engine oil during the warm-up phase, a 2-way valve and a junction can be added to control the coolant inlet temperature. It can draw cold coolant from radiators, hot from the engine, or a mixture of both.

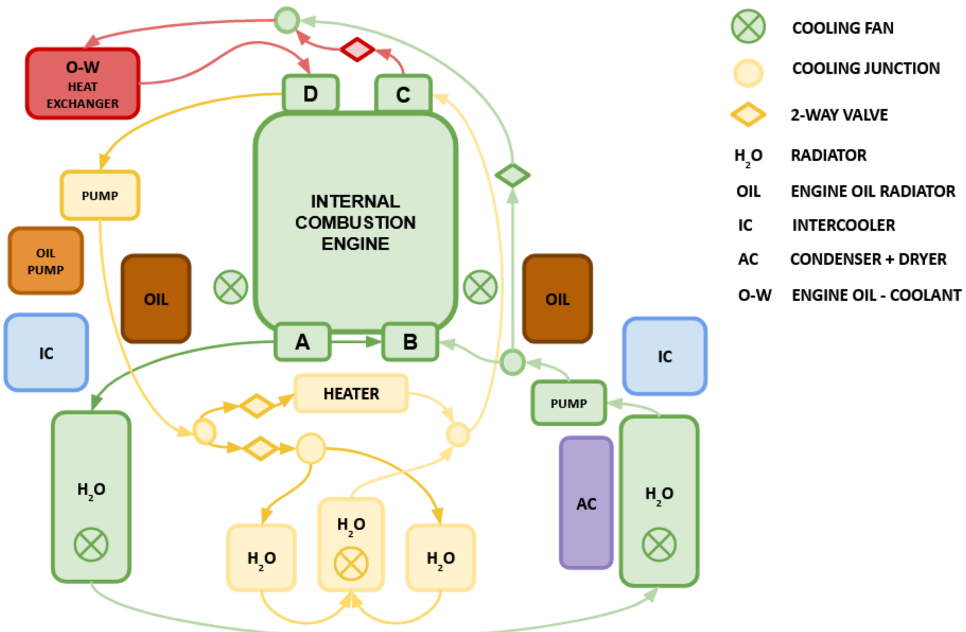

Figure 8-4: Cooling scheme with a more complex inlet circuit for the coolant into the heat exchanger.

8.2 Primary radiators development

The primary radiators of the car belonging to the green circuit are located inside the sidepods. One radiator per sidepod on either side of the car. It can be said that inside the sidepods, the radiators share the ambient airflow with the intercoolers and oil radiators. The presence of an oil radiator was a newly requested feature of the cooling system not present in the previous one. This by itself made the task of designing a higher cooling capacity than previous solutions challenging by lowering the available ambient airflow for the radiators. Moreover, the face area where the ambient air enters the radiator was lowered by 8% since the radiator's stack height had to be smaller for the intercooler to be bigger.

8.2.1 Coolant flow measurement

Taking advantage of the previous cooling system on a prototype car, in cooperation with my colleagues, the volume flow characteristic through a mechanical pump based on the engine speed was measured. It was done on a powertrain dynamometer using a non-invasive ultrasonic flow sensor attached to a coolant pipe of known cross-section. The configuration of the old cooling system, which was measured, was two radiators in series, each with a dual pass where the coolant is propelled only by a mechanical pump integrated into the engine. This configuration was developed based on experiments and experience, so it was needed to decide whether it was correct and if it could be improved using theoretical knowledge, data and calculations.

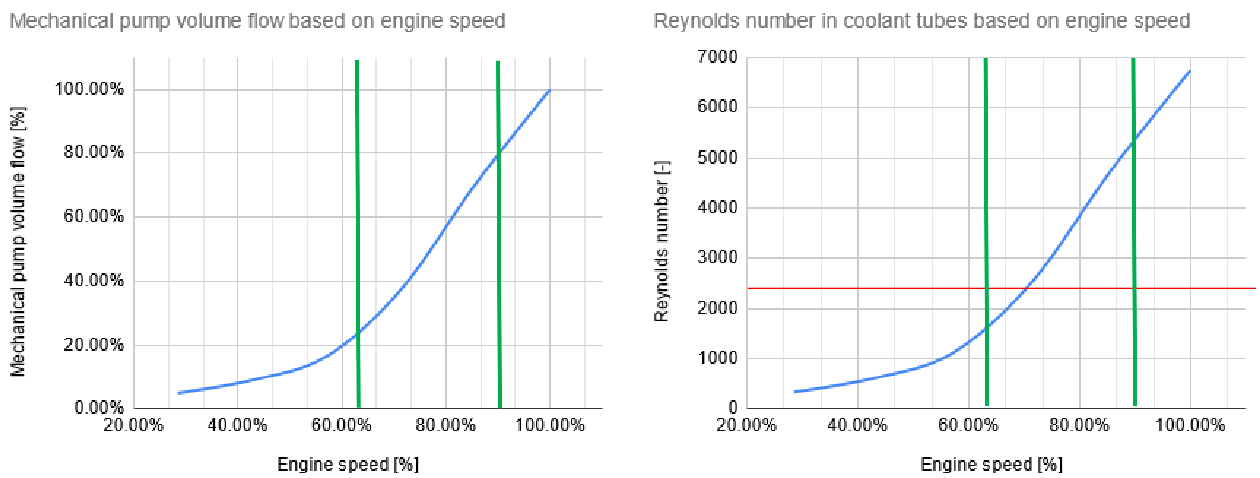

Figure 8-5: Measured mechanical volume flow across the circuit with primary radiators on the left chart. The right chart shows the volume flow converted to the Reynolds number of a coolant inside the radiator coolant tubes.

Figure 8-5 shows the measured volume flow through the green circuit coolant pipe based on the engine speed. 100% marks this configuration's maximum possible engine speed, therefore, maximum reachable flow rate. The two green vertical lines mark a region with the most represented flow rate on a racetrack where the prototype was tested. This race track has an average layout with low-speed corners, high-speed ones, and straights. Obviously, on different tracks, the green lines would have different positions. The driver's experience and driving style would also play a role. These boundaries were determined from the logged data of the car with the previous cooling solution. In the chart on the right is the calculated Reynolds number inside the radiator coolant tubes, where the red line marks the Re= 2300, which is the boundary between the laminar and turbulent regime. As said before, the transitional region is due to its complexity and the more general aim of the thesis neglected.

8.2.2 Pump performance curve

Before deciding whether the previous green circuit configuration was viable and whether it could be improved or should be reused, it is necessary to understand how it influences the cooling capacity. Moreover, the addition of an electrical pump for cooling down the car allows one to use it to achieve maximum cooling capacity as well.

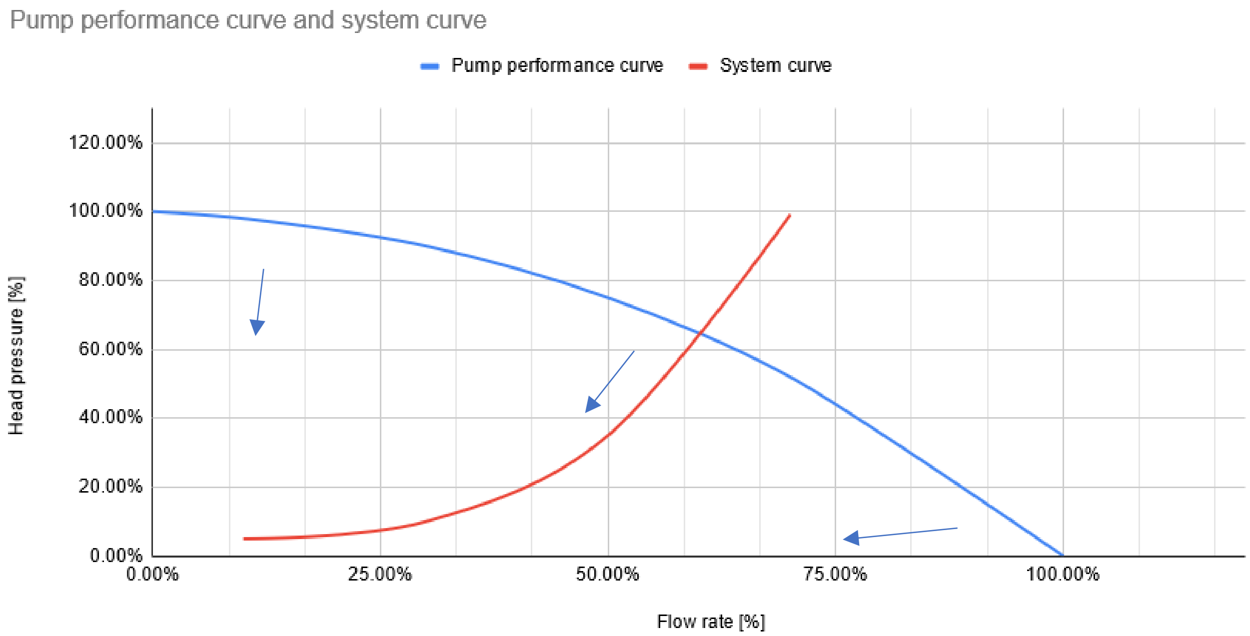

Figure 8-6: Representation of pump performance curve and a system curve where their intersection marks an operating point.

The representation of the pump flow curve can be seen in Figure 8-6. The head pressure is the height the pump can raise water to, and it is usually given as length or pressure. Flow rate marks the volume flow the pump can create at a given head pressure. Maximum head pressure is when the flow rate is 0, meaning the pump can only sustain water at a certain height, which can be viewed as hydrostatic pressure. The operating point is where this curve intersects with the system curve, representing how much pressure loss the pump must overcome within the closed system. The pressure loss is caused mainly by friction which is a function of velocity and various geometrical obstacles like bends and contraction of the end tanks and coolant tubes.

The arrows in Figure 8-6 represent the fact that the performance curve of the mechanical pump is dependent on the engine speed, and when it decreases, the whole performance curve follows and shrinks symbolically along the direction of said arrows.

Now it can be understood that the measured data in Figure 8-5 are the operating points for different engine speeds.

8.2.3 Pumps in series

Having an additional electric water pump on a green circuit requires understanding how the two pumps behave together. The electric pump can only be connected in series to the mechanical one due to the package envelopes and the engine's geometry.

Figure 8-7 represents the combined pump performance curve or so-called H-Q curve of 2 different pumps connected in series. H stands for head pressure, Q is the flow rate, and P1 and P2 are H-Q curves of pumps 1 and 2. This configuration increases the head pressure of the combined H-Q curve, which could yield a slightly more flow rate if the system curve is within the region where both pumps' heads are combined. As can be seen from the chart, if the two pumps have different H-Q curves, there is an area where only the work of pump 2 provides the system with a flow rate. If the pumps were placed in parallel, the opposite situation would appear where the combined flow rate increases, but the head pressure remains the same. Nevertheless, this configuration was impossible for the optimization concerning this thesis. [23]

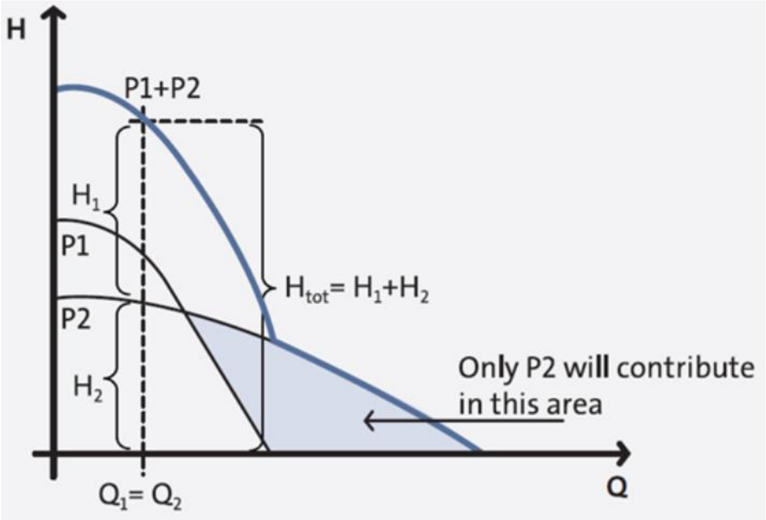

Figure 8-7: Two different-sized pumps connected in series. [24]

For the cooling scheme, pump one from Figure 8-7 can represent the electrical pump when the mechanical one, pump two, is operating with maximum engine speed. In this case, the electrical pump is not providing any boost to the flow rate since the intersection with the system curve is in a region which is directed only by the mechanical pump. On the contrary, an electrical pump can create unnecessary pressure loss due to its geometry.

The opposite situation is when the engine speed is low and, therefore, the H-Q curve of the mechanical pump is smaller. This can be represented as the area around the left vertical green line in Figure 8-5. In this case, pump 1 in Figure 8-7 would be mechanical, and pump two would be electrical. Knowing the H-Q curve of the electrical pump, it could be predicted that the electrical pump on maximum load would yield an operating point with around 40 to 50% of the maximum measured flow rate of the mechanical pump, as seen in Figure 8-5. If this pump operates on full load, it can be understood as a minimum coolant flow rate independent of engine speed or vehicle velocity.

8.2.4 Radiator configuration theory

Two variables influence the cooling capacity of the green circuit the most concerning the coolant flow and the radiator configuration.

The first one is the volume flow rate. Higher the value, the more cooling capacity the radiator can have. If, for example, the volume flow is only 10 l/min, then the coolant temperature would drop significantly as it flows through the radiator. This might seem like a good thing to have an outlet temperature from the radiator close to the ambient temperature, but in reality, most of the radiator provides no cooling capacity. The second thing is the coolant velocity in the coolant tubes and the Reynolds number, which depends on it. Achieving the turbulent regime is desirable for heat transfer, and having a large Reynolds number is beneficial to some point.

It may look simple that the higher the flow rate higher the Reynolds number given the same tube cross-section and the more cooling capacity the radiators can have. The first problem is that as the Reynolds number increases, its influence on the cooling capacity decreases. It is due to the limitation on the ambient air side, where it cannot take as much heat as the coolant can reject. At some point, the increase of Reynolds number by 10% yields only a 0.1% increase in cooling capacity. The opposite can happen, but in general, it is much easier to enhance the coolant side than the ambient air side.

The second fact is that the coolant velocity cannot be increased freely due to the less significant yet existing limitations on the coolant side, specifically concerning the coolant pump. For example, if a radiator with ten passes were made, the Reynolds number inside the radiator tubes would not be ten times higher compared to a single-pass radiator. Probably there would be almost no flow at all. Increasing the Reynolds number and the number of bends from the additional passes increases the pressure losses of the system. Therefore, as expressed using the H-Q pump curve, the flow rate decreases as the head pressure requirements increase.

It is necessary to find a configuration where the Reynolds number inside the radiator is high enough for good heat transfer but not excessively compared to the capability of the ambient air side to accept that heat. Also, it must be considered that not only a mechanical pump depends on engine speed and, therefore, partially on vehicle velocity. With low car velocity, for example, during cornering, the ambient air mass flow through radiators is limited similarly to the mechanical pump. Therefore it cannot take as much heat as if the car was going faster on a straight. This means that the low flow rate of the mechanical pump under these conditions does not equal a weak point in the cooling system since if the coolant were circulating faster, the ambient air would not be able to utilize the enhanced heat transfer. This, to some degree, implies that maybe the planned electrical pump is too powerful regarding the flow rate. But then again, one of the thesis aims is to find maximum cooling power, and assuming that a smaller electrical pump would be a better choice is questionable. The data from testing season should provide answers to this as well.

It is obvious that if the coolant tubes were larger, the volume flow inside the system would be higher, and the Reynolds number inside the tubes would decrease. It was not analyzed how could such a change influence the system since there was no option for different coolant tube cross-sections on the manufacturer's side. The same goes for adding turbulators inside them or increasing the surface roughness. Potentially decreasing the coolant tubes' inner height with a combination of added turbulators or higher surface roughness could lead to much faster fouling, which also cannot be confidently predicted.

It was requested to use a glycol and water mixture. However, a simple upgrade to the cooling capacity can be made if water with additives is used. In the same conditions, where the green circuit radiator 100% cooling capacity is evaluated, it could provide an additional 5.5% cooling capacity. Furthermore, this analysis does not consider the benefit of decreased pressure loss of the water inside the radiator tubes due to lower viscosity and density. Therefore, the benefit of that change would probably be higher.

8.2.5 Radiator configuration evaluation

For example, by switching from a series to a parallel radiator configuration, the volume flow in each radiator would be approximately halved. However, it would not be exactly half because with lower volume flow, the velocity in radiator tubes would be lower, and therefore the pressure losses would be lower as well. The lower pressure losses would mean lower requirements on pump head pressure and a higher flow rate.

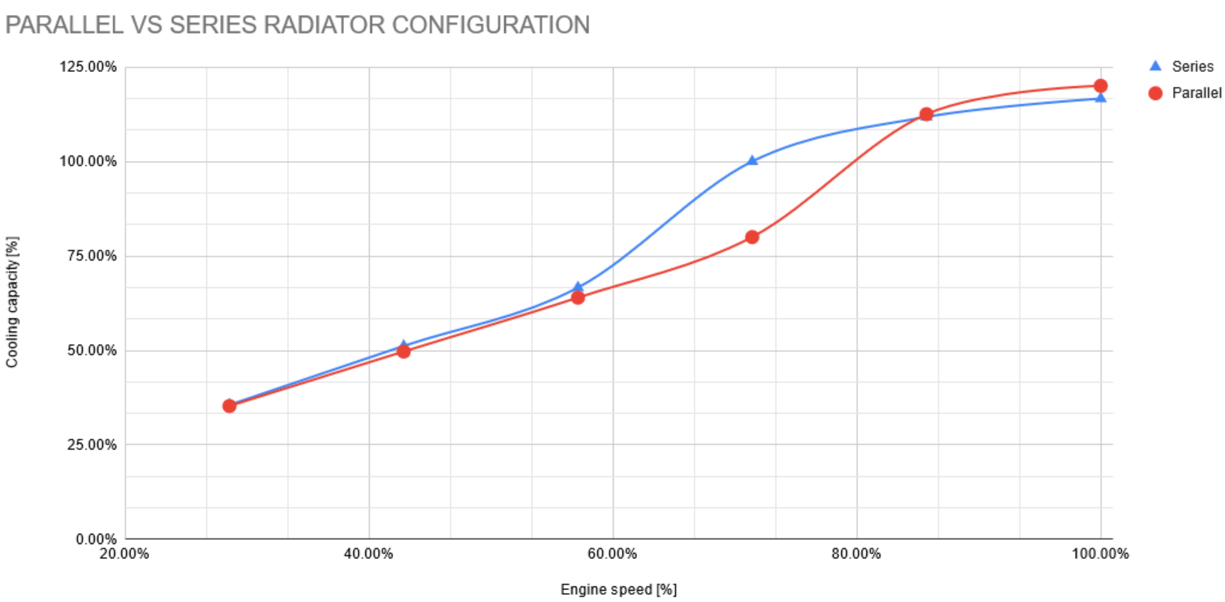

Figure 8-8: Comparison of parallel and series radiator configuration on cooling capacity based on engine speed.

Figure 8-8 suggests that the series configuration is inferior to the parallel one concerning the cooling capacity. Both radiators have dual passes with coolant flow circulated by the mechanical pump. While for the series configuration, the coolant flow was measured as discussed before. Minor adjustments had to be made for the parallel so that the flow rate was not halved but slightly higher. As mentioned, the steeper cooling capacity increase after 60-70% of maximum engine speed for series configuration is due to the transition from a laminar to a turbulent regime. Before the transition, both configurations have approximately a 15% increase in cooling capacity with each 14% increase in flow rate. In the turbulent regime, it can be up to a 33% increase in cooling capacity with a 14% increase in flow rate. This increase in cooling capacity is only around 5% for series and 7% for parallel, between 86% and 100% of the maximum measured flow rate. This is due to the limitations on the ambient air side, which are becoming more and more prevalent.

The flow rate of parallel configuration may be under-predicted. However, the transition into a turbulent regime happens later, at around 85% of the maximum flow rate for parallel configuration, while at around 70% for the series. Considering that the mechanical pump's most present coolant flow rate is between 63 to 90% of the maximum measured flow rate on the racetrack. The parallel configuration is worse than the series one because for most of the race track. The series configuration offers higher cooling capacity than the parallel configuration due to the differences between the laminar and turbulent flow despite the more equally distributed coolant temperature in radiators with the parallel configuration.

This suggests that keeping the former radiator configuration is wise. Figure 8-8 also shows the 100% in cooling capacity for series configuration, which is the 100% towards which the additional yellow circuit radiators will be related.

Switching from radiators in series with a dual pass to single pass ones in series configuration could fair similarly to previously discussed dual pass radiators in parallel. It could have a slightly higher flow rate due to the removal of additional pressure losses that occur in the dual-pass radiators. However, this slight potential increase in coolant capacity compared to the dual pass parallel configuration does not make it better than the original dual pass series configuration for the same reason I discussed concerning Figure 8-8.

Worse case would be a single pass in parallel where the coolant in the radiator would probably never achieve the turbulent regime with the current mechanical pump.

Making the radiators triple pass and keeping them in series could result in a slightly higher cooling capacity than the dual pass configuration if the coolant flow rate through the radiators would not decrease much. The triple pass was not selected as a solution because the cooling capacity increase would be below 5% for the best-case scenario.

Any more complicated configurations would probably not be beneficial. The increased pressure losses from additional passes would hinder the coolant flow rate through the radiator, and the cooling capacity would decrease.

8.2.6 Radiator design

As mentioned at the beginning of segment 8-2, the radiator stack height had to be smaller by around 6% to make room for the intercooler. The only way radiators could be made larger was to increase the thickness by 24% compared to the prototype solution. For the fin density, the maximum the manufacturer could provide was chosen. The decision was based on the CFD simulation data, including the data with the preliminary cooling solution. Due to the overall design of the sidepod and aerodynamic package of the car, the pressure in front of the radiator was higher than after the radiator on the sidepod outlet in a way that suggested that the pressure resistance of the radiator does not hinder the ambient airflow through it by much.

This is mostly correct when comparing the first to the second version of the new radiator. It has the same thickness as the preliminary radiator and a lower fin density than the first new radiator by 25%. Comparing both new radiators with the same conditions in CFD simulation, the ambient air mass flow across the thicker radiator core with denser fins was only around 10% lower than the more air-flow-friendly one.

The main reason for the second thinner and less dense radiator core was the new requirement of the cooling scheme, which was to have an AC condenser inside the sidepod. Using the second new radiator variant, the additional space seemed necessary for a larger clearance between the condenser and the radiator. While it is possible to place the condenser in front of the first thicker radiator, there could be problems with airflow across both devices. If the clearance is insufficient, the combination of heat transfer from the radiator into the condenser and restricted airflow could, in some cases, be limiting enough for the condenser to stop working. This would mean that the liquid used in air conditioning could not condensate. Therefore, the whole AC system would fail.

The thinner cores are not planned to be placed into both sidepods because, in similar conditions with dual pass series configuration, they have a cooling capacity lower by around 17% compared to the thicker ones. Arguably, the only viable option could be a combination of a thicker radiator core in one sidepod and the thinner core in the sidepod with the condenser. Whether this is necessary can only be confirmed during the testing on track.

Compared to the green circuit radiators of the preliminary prototype cooling solution, the new thicker radiators should offer a higher cooling capacity by 5%. It is not higher because of the worse ambient airflow conditions caused by the requirement of engine bay ventilation and making the intercooler larger at the cost of the radiator size.

8.3 Yellow circuit radiators

The yellow circuit radiators and heater are located in the front of the car. There are good airflow conditions for the radiators, which makes this place viable for cooling purposes. But there is not much space, meaning the radiators have to be relatively small compared to the ones in the green circuit.

The prototype cooling solution showed that the coolant flow from the engine to the heater and back was problematic without an electric pump. When the pump was added, the issue was solved. With the addition of three radiators, it was essential to determine if the pump could circulate the coolant through them and the approximate volume flow.

8.3.1 Flow rate experiments

Using a straightforward experiment with the electric pump, containers with water, radiators, pipes and stopwatch in cooperation with colleagues, the volume flow for different configurations of the radiators was approximately determined. To present experiment results, consider that the electric pump is working under full load without the need to overcome any pressure. Therefore, it will have a maximum volume flow of 100%, towards which the experimental results are related.

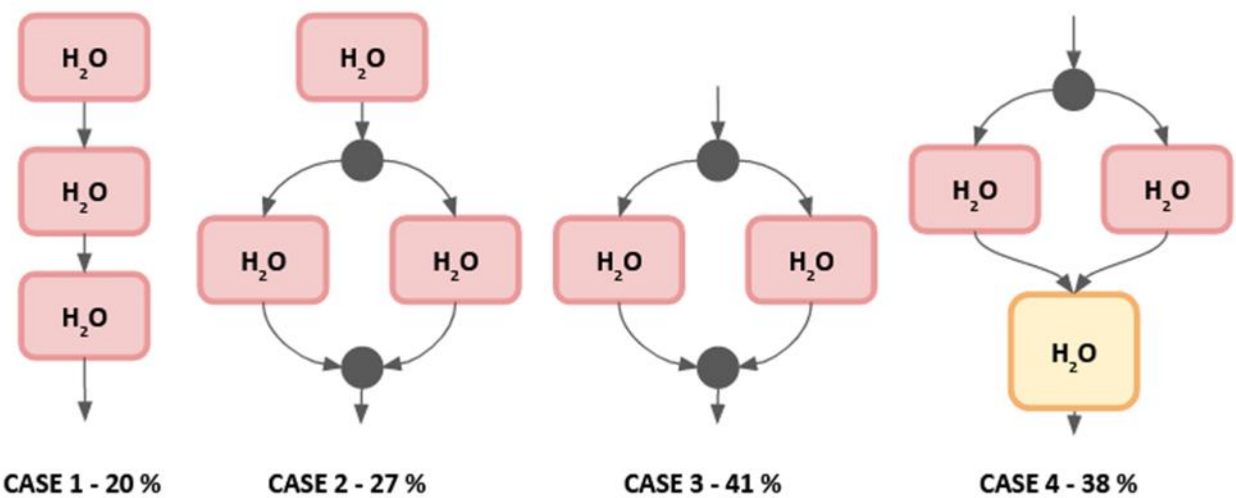

Figure 8-9: Results of selected cases of volume flow experiment where 100% marks volume flow of electric pump without any connected elements.

Figure 8-9 shows the results of 4 selected cases with different configurations. The red radiators are bought, and the yellow one is manufactured according to the specified parameters. The red radiators are smaller in size with fewer coolant tubes compared to the yellow one, meaning that due to increased coolant velocity, the pressure losses are higher. Therefore, the volume flow through the pump is lower. The experiment showed that setting the three red radiators in series would yield low-volume flow, and the semi-parallel configuration in case 2 would not improve it much. Therefore, there was a need for a larger custom-made radiator.

Comparing cases 3 and 4 confirms that this radiator does not significantly increase pressure loss. The size of the yellow radiator was based on the maximum available space. For the fin density, the highest value possible to manufacture was chosen since the combination of radiator thickness and CFD data suggested that there should be a pressure distribution and airflow to support it. The data below shows an estimated cooling capacity based on the measured flow rates related to 100% of the combined cooling capacity of green circuit radiators, which can be seen in Figure 8-8 for the series configuration. The results confirm that the decision to make a custom radiator for case 4 was correct. Comparing the yellow to the green circuit, it provides an additional 16,7% cooling capacity. Also, case 1, compared to case 2, shows higher cooling capacity with lower volume flow due to the different velocities inside the coolant tubes. In neither of these cases, the coolant was in a turbulent regime, which could not be changed due to pump size restriction.

Case 1 – 10,5% **Case 2 – 8,7%** **Case 3 – 11,2%** **Case 4 – 16,7%**

8.4 Intercooler

Due to slight changes in sidepod geometry, the intercoolers had to be made smaller, resulting in the flow length for charge air to be shorter by around 7%. On the other hand, at the expense of radiators, the stack height could be increased by 14%. For its thickness which is the flow length for the ambient air, packaging allowed its increase by 15%.

This increase in size was done to prevent potential problems which could arise from the planned increase of engine power achieved by higher boost pressure, which was a worry of some engineers within the company.

The intercooler cooling capacity at the same conditions, except for the sidepod geometry, was increased by 5% compared to the previous one. The main reason this increase is not higher is the decrease in ambient air mass flow through the intercooler core by 9%, caused mainly by the duct for the additional oil radiator. The intercoolers were not simulated with the same sidepod geometry because it would provide no valuable information since they are incompatible with the original solution. It might seem that the increase in core thickness could be the reason for the decrease in mass flow. However, the measurements of core characteristics of the pressure loss based on variable ambient air mass flow showed that the original thinner core is causing more airflow resistance than the new one.

For the intercooler, a second core was designed with around 25% lower fin density on the ambient side, which naturally causes less resistance to the airflow than the first core. Given the same conditions, the calculation showed a 2% lower cooling capacity than the first intercooler core with higher fin density. This once more suggests that in the current sidepod geometry, the cores with higher fin densities or larger core thicknesses are a better choice.

For the fin density on the charge air side, the previous core showed good compatibility regarding its pressure loss and turbocharger compressor performance curve. Combining this and the unknown pressure loss characteristics of the cores for the charge air side, the fin density was not changed. However, it can be said that the fin density on the charge air side is among the highest values the manufacturer can produce. By increasing the stack height of the new cores and their thickness while lowering the flow length, the cores are expected to have lesser pressure loss on the charge air side than the original core, given the same compressor-related conditions. This lower pressure loss should be helpful with the planned increase in engine power with higher boost pressure.

Besides the intercoolers, the end tanks, pipes and tubes from the turbocharger into the intercooler and from the intercooler to the inlet manifold were optimized. The diameter of the tubes was increased, and the end tanks were changed so that the path of the charge air is as smooth as possible from the aerodynamic perspective. The pressure losses should therefore decrease further. It cannot be estimated how significant an improvement was made due to the complex shapes of the end tanks. Originally they were made from metal sheets welded together. The new design required them to be made from 3D-printed aluminium.

8.5 Oil cooling system

The oil flow rate was not possible to measure at that time, which meant the calculation I could make only educated guesses. To have as much variability for the cooling system as possible, the additional oil radiators with their electric pump for oil are an important part of the system until the testing proves otherwise. The same goes for the proposed possible variable coolant temperature on the inlet to the heat exchanger, as seen in Figure 8-4.

The plate heat exchanger was chosen because it is a reasonably cheap yet capable solution compared to the micro matrix tube and fin heat exchanger mentioned in the research part of the thesis. It can also be scaled by adding more cooling plates if needed in the future. The heat exchanger I decided to implement was already an upscaled version of the OEM one used in the well-known sports car, which has a similar engine configuration with comparable power output.

8.6 Cooling fans

The primary cooling fans with the shroud cover part of the green circuit radiators. They are essential for providing ambient air for the condenser and the radiators during the cool-down process. Smaller fans are inside the engine bay with a shroud mounted on the additional oil radiator. If those radiators are removed, the fans will remain since their main function is ventilating the engine bay to prevent the accumulation of high-temperature air, especially around the turbochargers. The last fan can be optionally mounted on the custom-made, yellow circuit radiator to aid the cool-down process.

9. Conclusion

The objective of the research part of the thesis was to gather relevant knowledge of the different cooling system solutions used in road vehicles with internal combustion engines. The next task was to use the gathered knowledge and analyse how the cooling system of the Praga Bohema can be made and which components it should have.

The following segments summarized below show that those two objectives were fulfilled.

Initially, the various constraints originating from the practical implementation of the cooling system were presented. It was followed by a brief research of how the heat is transferred into the cooling system and why it needs to be regulated. This was done to present which components need thermal management and which challenges such a solution would need to overcome. The central part of the research focuses on obtaining knowledge about various cooling system components with their advantages, disadvantages and alternatives serving the same purpose. Most of the research focuses on devices for the thermal management of engine coolant and engine oil. The intercoolers, HVAC system, and supporting elements such as cooling fans are given less importance. This knowledge is used in discussing hypothetical vehicles operating in various relevant scenarios that differ in ambient temperature and operating conditions of said vehicles. It is concluded by analyzing how Bohema should operate in these scenarios and, therefore, which component its cooling system should have.

Recapitulating the most critical outcomes of the analysis, the radiators and intercooler should be made as large as the package allows with Tube and Fin design approach. The electric pump for the coolant and electric fans should be implemented to overcome the cooling down challenges. Coolant should be based on a water and glycol mixture for the car to drive and stay in a cold environment. A thermostat can remain purely mechanical, and a heater can depend on heated coolant from the engine. Oil thermal management should be done with the liquid-to-liquid heat exchanger with oil-to-ambient air radiators as support. Intercoolers should be directly cooled by ambient air. The radiators must be made in a way that allows placing the condenser for air conditioning in front of them.

The last and most important task was to develop a cooling system scheme for Bohema, where basic design parameters are based on calculations, with the aim of achieving the highest cooling capacity possible given the constraints presented at the beginning of the thesis.

It was accomplished in the second part of the thesis with the following steps.

For the calculations, a model for heat exchange was created. It uses the radiator's or intercooler's geometrical parameters, working fluid properties and flow rates to calculate the outlet temperatures and cooling capacity based on the inlet temperatures. This model with flow rates of working fluids obtained from experimental measurements and CFD simulations was used to determine, for example, if the two primary radiators should be placed in parallel or series configuration and whether they should be made as a single or dual pass. The radiators and intercoolers were designed based on the preliminary prototype cooling solution, its analysis, and the packaging constraints and manufacturing possibilities and limitations. Utilizing the conclusions determined by using the heat exchange model and analysing which components Bohema should have and how the vehicle should operate, the cooling scheme was developed. It is important to note that it was based on a preliminary prototype cooling system solution with the aim of removing its weak points and increasing its overall cooling capacity.

Summarizing the outcomes of the development of the cooling scheme and design of the radiators and intercooler, the following improvements were achieved.

The primary two radiators, also described as "green circuit radiators", offer at the same conditions regarding vehicle velocity, engine speed and inlet temperatures of working mediums an increased cooling capacity by 5% compared to the preliminary prototype solution for similar radiators. They are made as a dual pass with a series configuration.

New additional radiators, also described as "yellow circuit radiators", connected to the heater coolant circuit offer an additional 16,7% cooling capacity on top of the primary radiators. Therefore compared to the preliminary prototype solution for engine coolant, the cooling capacity was increased by 21,7%.

For the intercoolers given the same inlet temperatures of working mediums, vehicle velocity, and charge air mass flow, the cooling capacity was increased by 5% compared to the prototype solution. There is also the benefit of theoretically lower pressure losses for the charge air due to the changes in intercooler dimensions, the geometry of the end tanks and the increased diameters of the pipes and tubes for the charge air.

The engine oil thermal management was improved by using the plate heat exchanger with a semi-variable engine coolant temperature, which is the second working medium. Additional oil radiators support the system. Since the system was designed for high modularity, for example, by increasing the number of plates in the plate heat exchanger, the data from racetrack testing of the vehicle will be important to perfecting the system.

The engine bay ventilation through the sidepod with additional cooling fans was added to prevent heat accumulation. To what degree this will improve the cooling capacity or durability of the cooling system is uncertain. However, it is an important new aspect of the cooling system.

The cooling system cooling capacity can be further increased by replacing the water: glycol mixture with water and additives. For example, such a change would increase the primary radiators' cooling capacity by 5.5%, excluding the additional benefit of a higher coolant flow rate and subsequent cooling capacity increase. On the other hand, if the cooling capacity is larger than needed, the additional radiators or oil radiators can be easily removed to lower the weight.

Bibliography

[1] Praga history. *Praga* [online]. 2023 [cit. 2023-04-09]. Dostupné z: https://pragaglobal.com/praga-history/

[2] PRAGA BOHEMA. *Praga* [online]. 2023 [cit. 2023-04-09].

[3] Mazda's new SKYACTIV gasoline and diesel engines are steps on the road to its "Ideal Engine"; focus on compression ratio. *Green Car Congress* [online]. 2011 [cit. 2023-04-09]. Dostupné z: https://www.greencarcongress.com/2011/08/skyactiv-20110804.html

[4] HEYWOOD, John B. *Internal Combustion Engine Fundamentals: Second edition*. 2nd. USA: McGraw-Hill Education, 2018. ISBN 978-1-26-011611-3.

[5] *2016 Nissan GT-R Service Repair Manual: Engine Cooling System*. 2014.

[6] Engine Thermostat. *SaVRee* [online]. 2023 [cit. 2023-04-10]. Dostupné z: https://savree.com/en/encyclopedia/engine-thermostat

[7] MCKNIGHT, Bill. The Electrically Assisted Thermostat. *MOTOR* [online]. 2017 [cit. 2023-04-10]. Dostupné z: https://www.motor.com/magazine-summary/electrically-assisted-thermostat/

[8] TRACY, David. The Fascinating Reason Why NASCAR Engines Run So Hot. *Jalopnik* [online]. 2019 [cit. 2023-04-10]. Dostupné z: https://jalopnik.com/the-fascinating-reason-why-nascar-engines-run-so-hot-1835071544

[9] GIMENO, Patricia. The importance of a water pump impeller. *Dolz* [online]. 2022 [cit. 2023-04-10]. Dostupné z: https://www.idolz.com/en/2022/11/21/the-importance-of-a-water-pump-impeller/

[10] GIMENO, Patricia. Types of automotive water pumps. *Dolz* [online]. 2022 [cit. 2023-04-10]. Dostupné z: https://www.idolz.com/en/2022/12/15/types-of-automotive-water-pumps/

[11] Coolant Inline Valves. *Rheinmetall* [online]. 2023 [cit. 2023-04-10]. Dostupné z: https://www.rheinmetall.com/en/products/thermal-management/water/coolant-inline-valves

[12] Ethylene Glycol Heat-Transfer Fluid Properties. *Engineering ToolBox* [online]. 2003 [cit. 2023-04-10]. Dostupné z: https://www.engineeringtoolbox.com/ethylene-glycol-d_146.html

[13] Radiators. *Mezzo Technologies* [online]. 2021 [cit. 2023-04-10]. Dostupné z: https://mezzotech.com/radiators.html

[14] *Vehicle cooling: A compact guide for the workshop* [online]. Germany: MAHLE Aftermarket, 2021 [cit. 2023-05-13]. Dostupné z: https://www.mahle-aftermarket.com/media/homepage/facelift/media-center/klima/mah-kompaktwissen-ec-fahrzeugkuehlung-en-screen.pdf

[15] Plate Heat Exchanger: What is a Plate Heat Exchanger and How Does It Work. *HFM* [online]. [cit. 2023-04-11]. Dostupné z: https://www.hofmann-heatexchanger.com/plate-heat-exchangers

[16] The core - the heart of the heat exchanger. *Laminova* [online]. Think Automotive, 2023 [cit. 2023-04-11]. Dostupné z: https://www.laminova.com/technology/the-core

[17] Micro Matrix Heat Exchangers (MMX). *PWR Advanced Cooling Technology* [online]. 2023 [cit. 2023-04-11]. Dostupné z: https://www.pwr.com.au/products/micro-matrix-heat-exchanges-mmx/

[18] BELL, Corki. *Maximum Boost: Designing, Testing and Installing Turbocharger Systems*. 41097th edition. Cambridge (Massachuttes): Robert Bentley, 1997. ISBN 0-8376-0160-6.

[19] LEWIN, Andy. Bar & Plate vs Tube & Fin Intercooler. *BestCarsEssex* [online]. 2021 [cit. 2023-04-12]. Dostupné z: https://www.bestcarsessex.com/bar-and-plate-vs-tube-and-fin-intercooler

[20] The Great Debate: Air-to-air vs. Air-to-water vs. Refrigerated Intercoolers. *Mechanic.com.au* [online]. 2019 [cit. 2023-04-12]. Dostupné z: https://trade.mechanic.com.au/news/the-great-debate-air-to-air-vs-air-to-water-vs-refrigerated-intercoolers1

[21] *VDI Heat Atlas*. 2nd edition. Berlin: Springer Berlin, Heidelberg, 2010. ISBN 978-3-540-77876-9.

[22] BERGMAN, THEODORE, ADRIENNE LAVINE, FRANK INCROPERA a DAVID DEWITT. *Fundamentals of Heat and Mass Transfer*. 7th edition. Wiley, 2011. ISBN 978-0470-50197-9.

[23] Flow separation (boundary layer separation). *Tec-science* [online]. tec-science, 2020 [cit. 2023-04-29]. Dostupné z: https://www.tec-science.com/mechanics/gases-and-liquids/flow-separation-boundary-layer-separation/

[24] BALLUN, Jorie. How To Operate Centrifugal Pumps In Series Or Parallel. *Crane Engineering* [online]. 2015 [cit. 2023-04-30]. Dostupné z: https://blog.craneengineering.net/operating-centrifugal-pumps-in-series-or-parallel

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